DESIGN AND INTEGRATION OF A TRAILER HITCH FOR A HYDRAULIC HYBRID CHEVY EQUINOX

Final Report

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1 ABSTRACT

Rules for the Challenge X Competition, sponsored by General Motors and the United States Department of Energy, call for a trailer hitch with a towing capacity that meets the current baseline Chevy Equinox. The University of Michigan Challenge X Team's vehicle requires redesign of the trailer hitch due to relocation of other vehicle subsystems. Specifically, the new design must improve packaging by providing structural support for the fluid lines and by avoiding interference with the oil cooler and emissions equipment.

2 EXECUTIVE SUMMARY

2.1 Design Problem

The existing trailer hitch on the University of Michigan (U of M) Challenge X Team's vehicle was modified to an extent that the hitch was insufficiently connected to the chassis of the vehicle, and thereby unable to tow a trailer. This caused the team to be disqualified from trailering events in past Challenge X Competitions. Additionally, being a hydraulic hybrid, the vehicle had a hydraulic line located near the trailer hitch that the team was supporting temporarily with flexible, screw-tight, steel clamps. However, this method was unacceptable for a final, competition-ready vehicle. Thus, the purpose of this project was to redesign, manufacture, and test a trailer hitch to support the required 3500 lb trailering load and also to provide adequate support for the hydraulic line. The end goal was to create a working model of the redesigned trailer hitch for the U of M Challenge X Team to use in the May 2008 Road Rally Competition, which included obtaining a waiver due to competition constraints on trailer hitch modifications.

2.2 Specifications

The most critical engineering specifications in the development of our design were:

- Minimum trailering capacity of 3500 lbs
- Target of 6 bolts required for attachment between trailer hitch and vehicle
- Minimum clearance of 0.01 in. between trailer hitch and bumper
- Minimum clearance of 0.01 in. between trailer hitch and oil cooler
- Designed as an SAE Class II towing hitch

2.3 Concept Generation and Selection

We generated many concepts through multiple brainstorming sessions, organized these concepts into three sub-systems: middle bracket, end brackets/tubing, and hydraulic line attachments, and then created twelve different system variants from the best sub-system concepts, which were determined through sub-system Pugh charts. Based on a final system Pugh chart, we selected our alpha design, which featured a stock trailer hitch with unique hydraulic line clasping mechanisms that welded directly onto the trailer hitch. To address concerns for the structural integrity of the hitch, as well as ease of manufacturing and installation, we further developed the alpha design into our final design, which wraps around the cross-section of the trailer hitch instead of being welded directly to the hitch.

2.4 Final Design

The final design is comprised of two main parts: a stock trailer hitch and two hydraulic line attachments, located in optimized locations along the main bar of the trailer hitch, as shown in Figures 1 and 2. A full view of the hydraulic line attachment is shown in Figure 3.

Figure 1: Final trailer hitch design integrated into the hydraulic hybrid vehicle

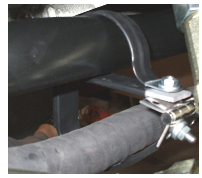

Figure 2: Attachment supporting hydraulic line in vehicle

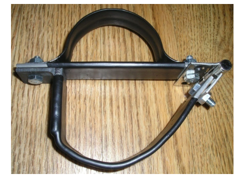

Figure 3: Manufactured hydraulic line attachment

2.5 Fabrication Plan and Cost Analysis

The process for manufacturing each of the hydraulic line attachments involved cutting, drilling, bending, welding, and sandblasting steel components in the ME 450 Machine Shop, and then applying rubber coating via a dipping process. The cost of one hydraulic line attachment is $9.76, and the cost of our entire redesigned trailer hitch is $190.58.

2.6 Test Results

All testing was completed successfully, thereby validating that our final design sufficiently meets all engineering specifications set forth based on the needs of our sponsor. These included corrosion testing and validating the hydraulic line attachment for supporting the weight of the hydraulic line.

2.7 Critique and Conclusions

The greatest strength of our design is that it has high potential for obtaining a competition waiver. The greatest weakness is that the rubber coating does not cover all areas of the metal hydraulic line attachments. To improve the project, we would have further investigated the potential for vehicle design changes and we would have streamlined the manufacturing process.

In conclusion, our redesign was successful. The finished trailer hitch with hydraulic line attachments will be installed in the U of M Challenge X Team's hydraulic hybrid for competition.

3 INTRODUCTION

In 2004, U of M was one of seventeen colleges and universities challenged by General Motors Corporation (GM) and the United States Department of Energy (DOE) to reengineer a Chevy Equinox, a crossover sports utility vehicle shown in Figure 4, as part of a competition entitled Challenge X: Crossover to Sustainable Mobility. As part of this competition, teams followed a hands-on engineering process based on GM's Global Vehicle Design Process, which aimed to teach them real-world engineering skills and make them highly valuable to the automotive community [1].

Figure 4: Hydraulic hybrid modified GM Chevy Equinox

The goals of the competition are to minimize energy consumption, emissions, and greenhouse gases, while maintaining or exceeding the vehicle's utility and performance specifications. After teams spent one year modeling, simulating, and testing the vehicle's powertrain and subsystems, GM donated a 2005 Chevy Equinox to each team. Teams then used the next two years to integrate their advanced powertrain and vehicle subsystems into the donated vehicles. In June of 2007, the teams came together to undergo extensive judging and evaluation based on their vehicle's energy use, emissions, utility, and performance. While the U of M team was not a top competitor in these events, it was the only team to successfully modify the Chevy Equinox into a hydraulic hybrid vehicle. Most teams used hybrid electric vehicle concepts.

Four years after the initial competition began, Challenge X is still motivating teams of students to think futuristically. The 2007-2008 academic year represents the fourth year of the competition. This year, Challenge X teams have been instructed to focus not only on further implementing innovative technologies into their vehicles, but also on meeting customer needs for safety, security, and convenience. In May of 2008, teams will once again bring their vehicles together in a Road Rally event to be thoroughly judged and evaluated.

3.1 Problem Description

To help achieve its goals for the upcoming road rally, the U of M Challenge X Team decided to sponsor our Mechanical Engineering senior design project. Our team has been tasked with redesigning, manufacturing, and testing a trailer hitch for the Chevy Equinox. Due to the extensive modifications the Challenge X Team has made to their vehicle, their original trailer hitch, shown attached to the vehicle in Figure 5, does not adequately support the hydraulic and oil cooler lines running underneath the vehicle.

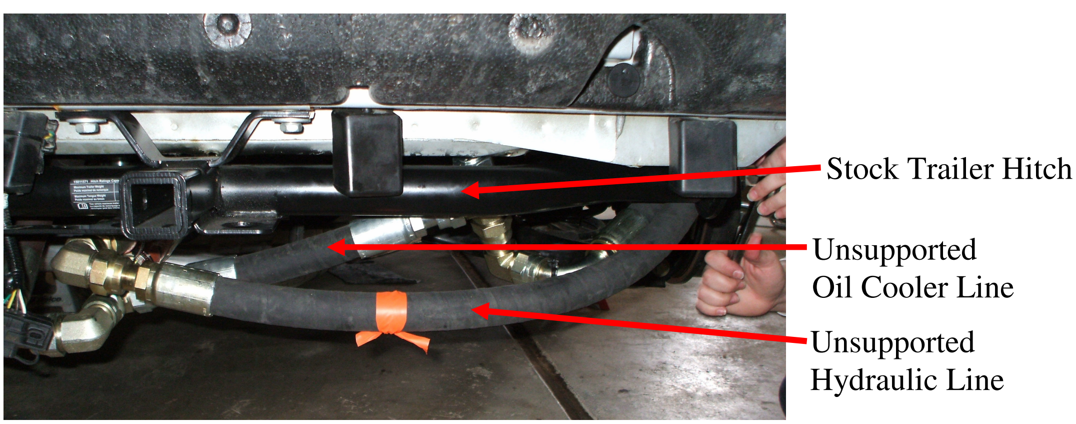

Figure 5: Stock trailer hitch on GM Chevy Equinox

Prior to our team's involvement with this project, the U of M Challenge X Team had modified their original trailer hitch to accommodate the location of a new oil cooler in the vehicle. These modifications, shown in Figure 6, were severe enough that that they were unable to tow a trailer because the hitch was insufficiently connected to the chassis of the vehicle (as shown in Figure 6). This inability caused the team to be disqualified from some of the past judging and evaluation events.

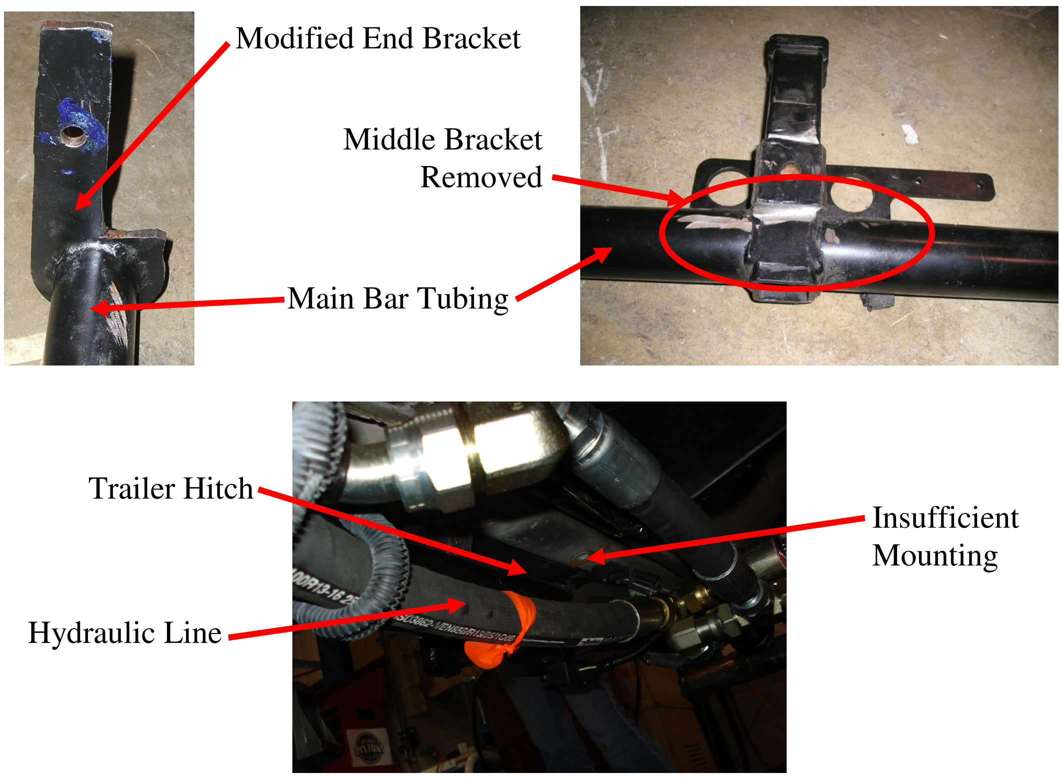

Figure 6: Original modifications to stock trailer hitch.

As our project progressed, vehicle design modifications made by the U of M Challenge X Team changed the mounting location of the oil cooler underneath the vehicle. This modification, combined with the flexibility of the fluid lines, allowed a stock trailer hitch to be reattached to the vehicle. A stock trailer hitch, however, still provided inadequate support for the fluid lines underneath the vehicle. The U of M Challenge X Team's temporary method for supporting the lines using flexible, screw-tight steel clamps is shown in Figure 7.

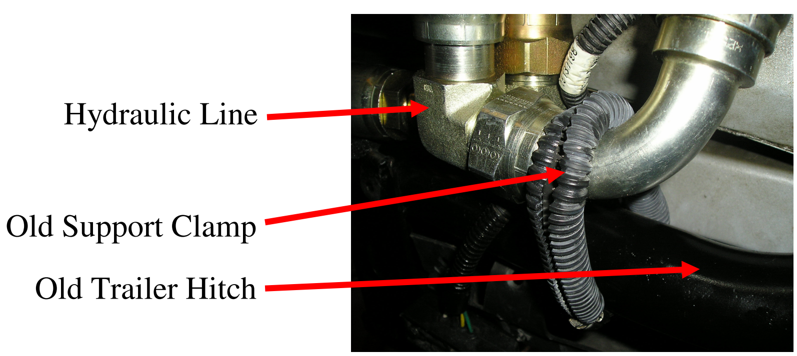

Figure 7: Temporary method of supporting fluid lines.

As indicated in Figure 8, the hydraulic line is located directly underneath the reinstalled stock trailer hitch, while the oil cooler line is located farther away. The oil cooler line is very secure, due to its rigid end attachments and short length (5.5 inches) between these attachments (see Figure 9). Therefore, the oil cooler line does not require support from the trailer hitch.

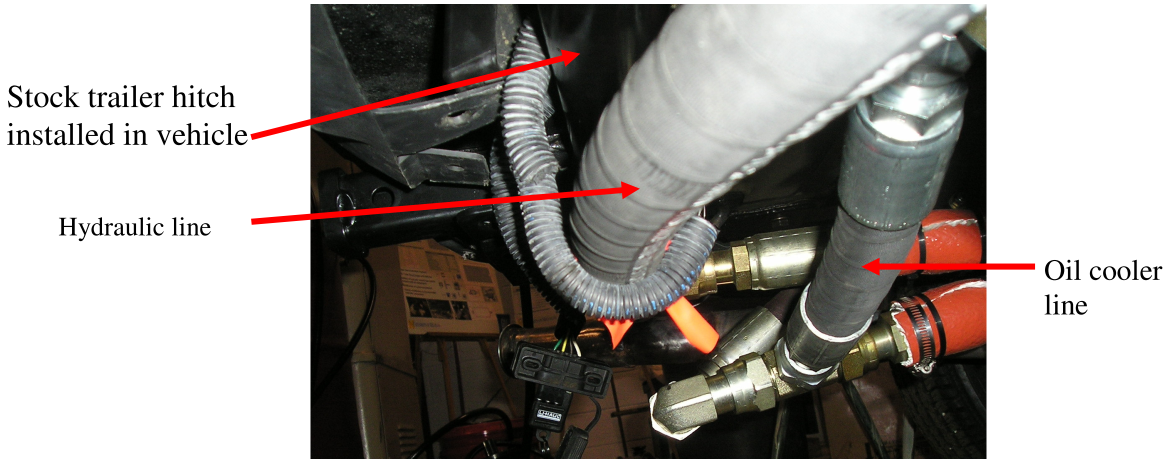

Figure 8: Relative locations of trailer hitch and fluid lines

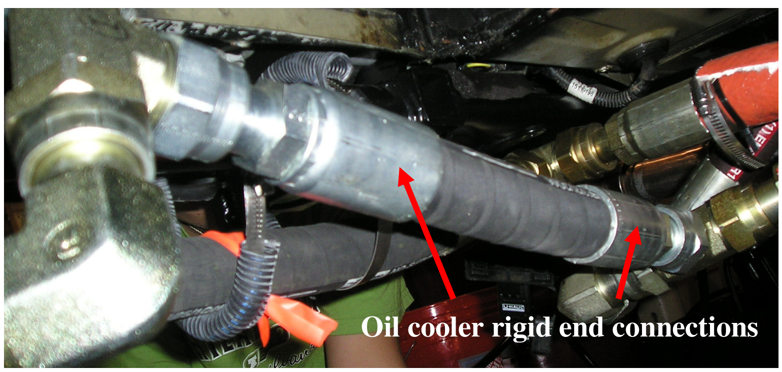

Figure 9: Oil cooler line

At the Road Rally in May of 2008, the U of M Challenge X Team will once again need to use a trailer hitch on their vehicle to meet certain towing requirements and specifications. Another disqualification from this portion of the events is not acceptable. Since the U of M Challenge X Team has only a few active members, meeting their goal of redesigning, testing, and manufacturing a new trailer hitch that adequately supports the hydraulic line would have been difficult without outside assistance. Therefore, the overall outcome of our project was to redesign and manufacture a trailer hitch for the U of M Challenge X Team to use in the May 2008 Road Rally competition.

3.2 Customer Needs and Project Outcomes

The broad project outcome of redesigning and manufacturing a trailer hitch was segmented into several components based on the needs expressed by our customer, the U of M Challenge X Team. To determine these needs, our ME 450 team developed a series of questions related to the trailer hitch project. These questions and notes from our first sponsor meeting are listed in Appendix A. Based on the answers from our sponsor, we determined the project requirements for our design. These project requirements, along with the reason for each requirement, are listed in Table 1.

Project Requirement	Reasoning
No interference with other components	The redesigned trailer hitch cannot interfere with the specified positions of the oil cooler, exhaust system, or any other vehicle subsystems.
Capable of sustaining load at stock trailering capacity	To compete in Challenge X Competition events, the trailer hitch must be able to carry a 3500 lb load.
Meets standard SAE trailer hitch sizing specifications	Trailer hitch must comply with size specifications so that standard trailers can be towed using the new design.
Able to structurally support hydraulic line	The customer has specified a desire that the redesigned trailer hitch incorporate support for the hydraulic line.
Lightweight	The Challenge X Competition rules specify a maximum allowed vehicle weight. Also, weight reduction improves fuel economy and emissions.
Working model manufactured and tested prior to Road Rally	Customer needs to use trailer hitch for Road Rally competition in May 2008.
Electrical wiring is operable	Challenge X Competition requires electrical components of trailer hitch to be in working condition.
Uses already-manufactured attachment points	Customer desires use of current holes in vehicle structure used for previous trailer hitch attachment because drilling additional holes could decrease the structural stability of the vehicle. If more holes are drilled, additional reinforcement will be required.
Easy to manufacture	The trailer hitch must be manufactured by our team using the resources provided through ME 450.
Easy to assemble and attach	Customer may need to attach and remove trailer hitch multiple times during vehicle development. Therefore, customer needs to be able to assemble and attach the trailer hitch in a timely manner without requiring special tools or excessive force.
Low cost	Project has an ME 450 budget constraint of $400. Additional funding from the U of M Challenge X Team is possible, but must be justified.
Meets GM's rear crash specifications	Challenge X vehicles are driven on surface roads, therefore they must be crashworthy.
Minimal modification to bumper design	Trailer hitch redesign is constrained by fixed bumper location. Small amount of material can be removed from underside of bumper, but Challenge X Competition awards points based on appearance and use of stock components.
Aesthetically pleasing	Challenge X Competition awards points based on appearance.

Table 1: Reasoning for selection of project requirements.

In addition to the project requirements outlined in Table 1, our team investigated the need for and process of obtaining a competition waiver that would allow the U of M Challenge X Team to compete in the trailering competitions. Since competition rules prohibit modification of any kind to the stock trailer hitch, our team had to show that our trailer hitch modifications did not hinder the original functionality of the stock trailer hitch in any way, or the U of M Challenge X Team would still be unable to participate in trailering events [15]. Further information on this waiver is provided in Section 16.8.

4 SPECIFICATIONS

Upon developing the project requirements stated in Section 3, we organized the requirements as customer needs in our Quality Function Deployment (QFD) matrix shown in Figure 10.

System QFD

Notation:
Blank = Not correlated
1 = Slightly correlated
3 = Somewhat correlated
9 = Highly correlated

	Trailer hitch weight	Designed as SAE Class II towing hitch	Clearance between oil cooler and trailer hitch	# of bolts required for attachment	Clearance between bumper and trailer hitch	Material yield strength	Trailering capacity	Sustains live load	Working model tested and verified by April 10	Steps in manufacturing process	# of points attaching each line to trailer hitch	Procurement, material, and testing costs	Mass reduction during corrosion testing
Trailer hitch weight													
Designed as SAE Class II towing hitch	1												
Clearance between oil cooler and trailer hitch													
# of bolts required for attachment	3												
Clearance between bumper and trailer hitch			9										
Material yield strength	1												
Trailering capacity	1			9									
Sustains live load	3	9		3		9							
Working model tested and verified by April 10	1			3									
Steps in manufacturing process													
# of points attaching each line to trailer hitch	1	1		1			1						
Procurement, material, and testing costs			1		1				9		3		
Mass reduction during corrosion testing								3		9		9	
Zero circuit malfunctions during testing	1		3	1	3			1					

Customer Needs	Customer Weights (10 = Highest Priority; 1 = Lowest Priority)	Trailer hitch weight	Designed as SAE Class II towing hitch	Clearance between oil cooler and trailer hitch	# of bolts required for attachment	Clearance between bumper and trailer hitch	Material yield strength	Trailering capacity	Sustains live load	Working model tested and verified by April 10	Steps in manufacturing process	# of points attaching each line to trailer hitch	Procurement, material, and testing costs	Mass reduction during corrosion testing	Zero circuit malfunctions during testing
		Engineering Specifications													
No interference with other components	10			9		9									
Sustains load at stock trailering capacity	9		3		3		3	9						3	
Meets standard SAE trailer hitch sizing	9		9					9							
Able to structually support hydraulic lines	8				3		3		9					3	
Lightweight	8	9			1		1						3		
Working model tested prior to road rally	7		1							9					
Electrical wiring is operable	7									3					9
Uses already-manufactured attachment points	6			3	9	3									
Corrosion resistant	5						1				1	3	9	9	
Easy to manufacture	5	1									9	3		1	
Easy to assemble and attach	4	1		3	9	3						9			
Meets GM's rear crash specifications	3			1	1	1	1								
Minimal modification to bumper design	2			1	1	9						3			
Low cost	1	3											9		
Aesthetically pleasing	1					9								1	
	Raw score	84	115	125	154	150	67	162	72	84	50	72	78	102	63
	Scaled	0.519	0.71	0.772	0.951	0.926	0.414	1	0.444	0.519	0.309	0.444	0.481	0.63	0.389
	Relative Weight	6%	8%	9%	11%	11%	5%	12%	5%	6%	4%	5%	6%	7%	5%
	Rank	7	5	4	2	3	12	1	10	7	14	10	9	6	13
Requirement Benchmarking	Equinox	26.5	II	n/a	6	>0.01	60	3500	*	n/a	6	n/a	**	<30	0
	Liberty	35	III	n/a	6	>0.01	50	5000	*	n/a	>3	n/a	**	<30	0
	Escape	26	II	n/a	6	>0.01	60	3500	*	n/a	8	n/a	**	<30	0
	Direction	(-)	T	(+)	(-)	(+)	(+)	T	(+)	(-)	(-)	T	(-)	(-)	(-)
Engineering Specification Units		lbs	SAE Class	inches	# bolts	inches	ksi	lbs	lbs	date	steps	attachment points	US Dollars	% mass	# of malfunctions
Engineering Specification Targets			II					3500							
Engineering Specification USL		27			6					4/10/08	10	4	$400	30%	0
Engineering Specification LSL				0.01		0.01	60		10						

* This number is unknown by benchmarking manufacturers.
** This number was not divulged due to privacy reasons.

Figure 10: QFD matrix showing correlations between project requirements and engineering specifications

To determine the relative importance of these project requirements, we used a 1 through 10 ranking system with 10 being most important and 1 being least important. As a group, our team read all of the project requirements and determined a rank value for each requirement based on our sponsor's desires. Some requirements were given the same level of importance because they were of equal priority to our sponsor.

Next, we translated these project requirements into engineering specifications by developing quantitative measures related to each requirement. By collaborative effort, our team read each of the project requirements and discussed how it could be measured, thereby generating a list of technical requirements. As a check, when we incorporated these engineering specifications in our QFD, we compared them with our project requirements to ensure that each project requirement was related to at least one of the engineering specifications we had developed.

At one point in our design process, we had also included specifications for crash requirements, specifically the amount of allowable fuel spillage in a crash event, based on National Highway Transporation Safety Administration (NHTSA) standards (see Section 16.7). However, as shown in Figure 11, the fuel tank is located much farther forward in the vehicle than a standard fuel tank. Due to this distance and the location of the rear axle between the trailer hitch and the fuel tank, we determined that in a crash event, fuel spillage caused by the trailer hitch was not a concern in this application. Therefore, we eliminated these engineering specifications.

Figure 11: Fuel tank location relative to trailer hitch

Next, we determined the correlations between our customer needs and engineering specifications, represented numerically in the middle section of the QFD. We then went through each combination of requirements and determined the magnitude of correlation between the two. Similarly, we determined the relative correlations between our engineering specifications as shown in the top section of the QFD. Based on this information, we used our QFD spreadsheet to calculate the relative weight and rank of each engineering specification, as outlined near the bottom of the QFD.

To complete our QFD matrix, we also conducted benchmarking activities to investigate competitive products. Since the stock vehicle was a Chevy Equinox, we decided to use the trailer hitch on this vehicle as one of our benchmarks. According to the Chevrolet website, the Chevy Equinox is comparable to the Jeep Liberty and the Ford Escape. Therefore, we used the trailer hitches on these vehicles as additional benchmarks [10]. Based on our engineering specifications, we developed a list of benchmarking questions about the trailer hitches on these vehicles. Then, we contacted the trailer hitch engineer working on each of these vehicle platforms at their respective corporations to gather our benchmarking information. These questions and data are detailed in Appendix B and summarized in the QFD.

One of the notable results of our benchmarking was that the hitch size of the Jeep Liberty was Class III, while both the Chevy Equinox and Ford Escape had Class II trailer hitches. This corresponds to the higher trailering capacity and weight of the Jeep Liberty. Therefore, we selected target values closer to the specifications of the Ford Escape. Additionally, a common feature among the benchmarked trailer hitches is that all three attached to the chassis in a similar six bolt fashion.

Finally, as a result of the ranking system and requirement correlations in our QFD, we were able to determine the order of importance of our engineering specifications. This order is given by rank of most important to least important in Table 2 below. As shown, specifications of equal importance received the same rank.

1	Minimum trailering capacity of 3500 lbs
2	Target of 6 bolts required for attachment between trailer hitch and vehicle
3	Minimum clearance of 0.01 inches between bumper and trailer hitch
4	Minimum clearance of 0.01 inches between trailer hitch and oil cooler
5	Designed as an SAE Class II towing hitch
6	Percent material weight lost during corrosion testing
7	Maximum trailer hitch weight of 27 lbs
7	Working model tested and verified by April 10
9	Maximum of $400 for procurement, material, and testing costs
10	Sustain live load of 15 lbs
10	Maximum of 4 points attaching fluid line to trailer hitch
12	Target material yield strength of 60 ksi
13	Zero malfunctions during electrical component testing
14	Maximum of ten steps in manufacturing process

Table 2: Engineering specifications for trailer hitch design

5 CONCEPT GENERATION

To develop numerous unique concepts for our trailer hitch design, we brainstormed as a team and with others. We also used functional decomposition to separate our overall function into three sub-systems: middle bracket, end brackets/tubing, and hydraulic line attachments (see Figure 6). In addition to these specific sub-systems, we originally generated ideas for modifications to the electrical box connection and safety chain attachments, but these changes were not explicitly related to our customer requirements and the ideas were not taken any further.

5.1 Concept Generation Process

The brainstorming session with the team involved coming up with and verbalizing ideas as they were conceived. We then took these ideas to our colleagues to develop ideas for the middle bracket, end brackets/tubing, hydraulic line attachment, and electrical box/line connection. In both brainstorming sessions, we did not make restrictions based on material, feasibility, time, cost, etc. The ideas generated by these brainstorming sessions are detailed in Section 5.3 and Appendix C.

5.2 Functional Decomposition

Based on our sponsor-defined problem and our literature review, the overall function required for our trailer hitch design was: To economically carry a 3500 pound load to allow the Chevy Equinox to safely tow a trailer, while maintaining crash worthiness, and compete in Challenge X competitions. We decomposed this overall function into five sub-functions as detailed below and shown in the function tree in Figure 12.

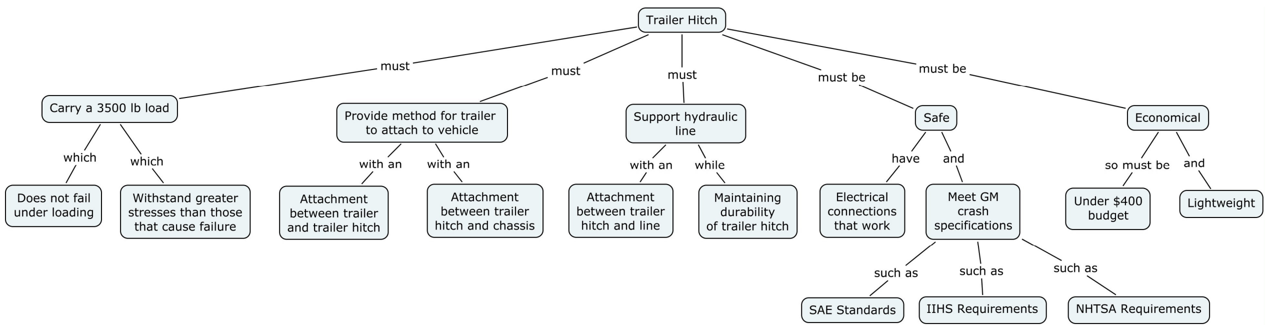

Figure 12: Function tree showing the details of each sub-function identified for the trailer hitch

The first sub-function was that the trailer hitch needs to carry a 3500 pound load during the Challenge X competition. While carrying this load, the trailer hitch had to provide enough support so it would not fail under loading and would withstand greater stresses than those that cause failure. If the trailer hitch did not meet this function, our design did not meet our customer needs. The second sub-function was to provide a method for the trailer to attach to the vehicle. This included providing an attachment between the trailer and trailer hitch, as well as an attachment between the trailer hitch and chassis. The third sub-function was that our trailer hitch had to support the hydraulic line running under the vehicle. More specifically, the hitch needed to provide an attachment for the line while providing enough durability to withstand their weight. The fourth sub-function was that our trailer hitch had to meet safety requirements. This sub-function consisted of providing a connection for electrical signals from the vehicle brake lights to the trailer brake lights and meeting all GM crash specifications, in order to allow the vehicle to act safely during a crash situation. GM crash specifications included meeting Society of Automotive Engineers (SAE) standards, Insurance Institute for Highway Safety (IIHS), and National Highway Transportation Safety Association (NHTSA) requirements (see Sections 16.5 and 16.7). The fifth sub-function was that the design had to be economical. This meant the design needed to provide a lightweight solution to our sponsor-defined task of supporting the hydraulic line, and also, the cost of our project was limited to $400.

5.3 Initial Concepts

This section details six of the design concepts developed during our brainstorming sessions and functional decomposition for the middle bracket, end brackets/tubing, and hydraulic line attachments. The rest of the ideas are shown in Appendix C.

5.3.1 Middle Bracket Concepts

The top two concepts for the middle bracket sub-system were to use the original middle bracket or a piece of square tube stock. Sketches of these two concepts are shown in Figure 13.

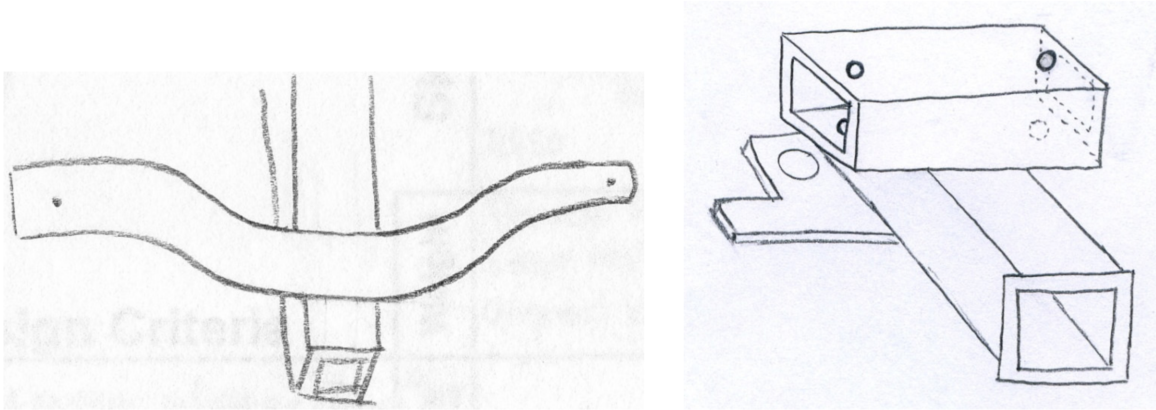

Figure 13: Original middle bracket (left) and square stock middle bracket (right) concepts

The original middle bracket design was to use flat steel, bent to allow the bolt holes to reach the current body attachment points. The square stock bracket concept was to use hollow square stock cut to fit the length of the current bracket. The dimensions and wall thickness of the square stock would have been determined by Finite Element Analysis (FEA) analysis and would use the current body attachment holes using long bolts.

5.3.2 End Brackets and Tubing Concepts

The top two concepts generated for the end brackets and tubing design were the original and thumbs-up trailer hitch designs, which both featured a curved main bar. These two concepts are shown in Figure 14. Due to geometry constraints, the tubing design was determined by the design of the bracket.

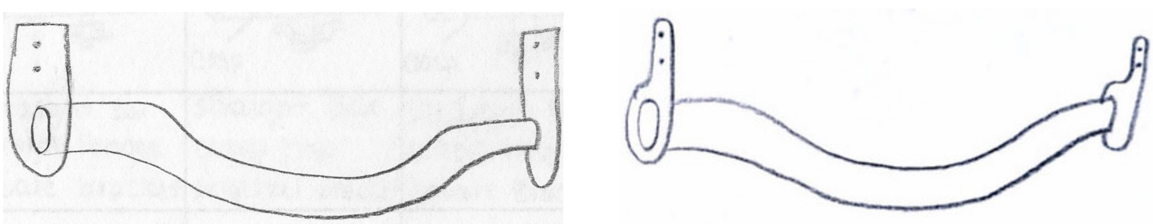

Figure 14: Original (left) and thumbs-up (right) end bracket concepts

The original design for the end bracket used a stock trailer hitch purchased from GM. The thumbs-up design would have been welded around the end of the hollow circular tube of the original stock tube, as a concept for decreasing component weight. We also came up with concepts that used a straight main bar; however, these concepts were more manufacturing intensive. Such additional concepts are shown in Appendix C.

5.3.3 Hydraulic Line Attachment Concepts

The top two concepts we generated for the hydraulic line attachments were the hinge and clasp designs shown in Figure 15.

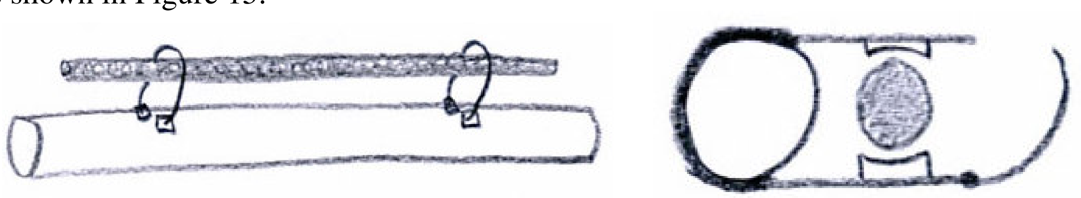

Figure 15: Hinge (left) and clasp (right) hydraulic line attachment concepts

The hinge concept used a hinge and catch mechanism to allow multiple uses. The bar consisted of rubber reinforced-rods welded to the hinge and catch. Rubber was chosen as an inexpensive method for protecting the hydraulic line from rubbing onto the metal of the hinge.

The clasp concept was a large loop, welded to the trailer hitch on one end. On the other end, there would have been a hinge that allowed the hydraulic line access into the loop. The concept also featured optional cushion supports to prevent the hydraulic line from rubbing against the metal components.

6 CONCEPT SELECTION

After our concept generation phase, we focused on our ideas for each of the three sub-systems: middle bracket, end brackets/tubing, and hydraulic line attachments. Then, we used a go/no go screening process to assess the feasibility of each proposed concept. We eliminated ideas based on conditions such as geometric constraints, manufacturing difficulties, and design ineffectiveness. Then, using the concepts we deemed fit to continue in the selection process, we created a Pugh chart for each sub-system to determine the best component concepts. These three Pugh charts are shown in Appendix D.

Finally, by combining these best component concepts, we created twelve different system variants and ranked the concepts in a final Pugh chart. Figure 16 shows this Pugh chart for the top five concepts, and is followed by a short discussion of the advantages and disadvantages of each concept. The selection matrix for the seven other concepts is given in Appendix D.

Trailer Hitch System Variants	**Weight**	**Design #1**	**Design #5**	**Design #3**	**Design #7**	**Design #2**
Design Criteria		Orig. Bar Hinges Orig. Bracket	Thumbs Up Hinges Orig. Bracket	Orig. Bar Clasps Orig. Bracket	Thumbs Up Clasps Orig. Bracket	Orig. Bar Hinges Sq. Bracket
No interference with other components	1.6	+	+	-		0
Sustains 3500 lb load	1.6	+	0	+		+
Structurally support hydraulic lines	1.3	-	-	0		-
Lightweight	1.3	+	+	-		0
Working model tested by April 15	1.1	+	0	+	D	0
Corrosion resistant	0.8	+	+	0	A	-
Easy to manufacture	0.8	+	+	+	T	+
Easy to assemble and attach	0.6	0	0	0	U M	-
Meets GM's crash specifications	0.5	+	0	+		0
Minimal modification to bumper	0.3	+	+	0		0
Low cost	0.2	+	+	0		+
Aesthetically pleasing	0.2	+	+	0		0
Total Points	1	8.13	5.00	3.91	0	2.50
	0	0.63	3.75	3.28	10	4.84
	-1	1.25	1.25	2.81	0	2.66
		6.88	3.75	1.09	0	-0.16
Rank		1	2	3	4	5

Figure 16: System Pugh chart showing the top five concepts for overall trailer hitch design

As indicated by our system Pugh chart, our top concept was Design 1, which received significantly more positive points than all other concepts. This design used the main bar and the middle and end attachments from the original trailer hitch, with the addition of rubber-coated hinge attachments for hydraulic line support. This design was advantageous because the original trailer hitch had already been tested and verified by GM, making it more likely for the Challenge X Competition to approve a waiver request for a minimal modification to the original trailer hitch. Also, the design was easier to manufacture than any of the other designs, it utilized all of the original bolts, and it was the second most lightweight concept. However, the design was disadvantageous because we predicted the rubber-coated hinge attachments to be less structurally supportive of the hydraulic line than the clasp attachment. Also, welding the hinge to the main bar of the trailer hitch could decrease the structural integrity of the tubing.

Our second-ranked concept was Design 5. This concept was similar to the top design, with the difference being the thumbs-up end attachment idea. This concept was advantageous because the end attachment would have a reduced amount of material, making the trailer hitch lighter in weight. However, this material reduction could compromise the hitch's ability to sustain the 3500 lb load and was not proven to be valid under GM's crash specifications, which would have made it more difficult to obtain a waiver from the Challenge X Competition.

The third best concept was Design 3. This design used the original main bar, end and middle attachments, and incorporated the padded, clasped fluid line supports. This design was advantageous because, again, it used the original, validated, trailer hitch and added on the attachments for hydraulic line support. However, it was disadvantageous because the clasped attachments would be welded around the tube of the trailer hitch, and this added thickness could cause an interference with the rear bumper. Furthermore, due to the complex geometry of the clasped attachments, these mechanisms would have been more difficult to cover in corrosion-resistant coating. Also, these attachments would have added more weight than the rubber-coated hinges.

The fourth-ranked concept was Design 7, which used the original middle bracket and main bar design, with thumbs-up end attachments and the clasped hydraulic line attachments. In our selection process, we chose this design as our datum. Although this design had the advantage of reduced weight in the end attachments, the addition of the clasped line attachments were anticipated to result in a net gain in weight. This design had the same disadvantages associated with the clasped attachment as stated for the third top concept, with the further disadvantage of not being GM-validated, due to the alteration of the end attachments.

Finally, the fifth best concept we proposed was Design 2. This concept used the original main bar and end attachments, with the rubber-coated hinges for hydraulic line support and the square tube concept for the middle attachment. The middle attachment was the only difference between this design and the top concept. The advantage of this design was that it still would have been relatively easy to manufacture, since the middle attachment was just a piece of square tube stock, with holes, welded to the trailer hitch receiver. However, this difference would have required much more analysis and validation to prove it could support the 3500 lbs and meet GM crash specifications. Also, the square stock would have been less aesthetically pleasing than the original middle bracket attachment.

As indicated by this discussion, the concept rankings determined by our selection process made sense, based on our customer and engineering requirements. The top design, our alpha design, is described in further detail in the following section.

6.1 Alpha Design

Our team's alpha design used the current trailer hitch attachments for the middle bracket and end brackets/tubing, along with newly designed hinges for the hydraulic line attachments. Two overall views of the redesigned trailer hitch are shown as CAD models in Figure 17.

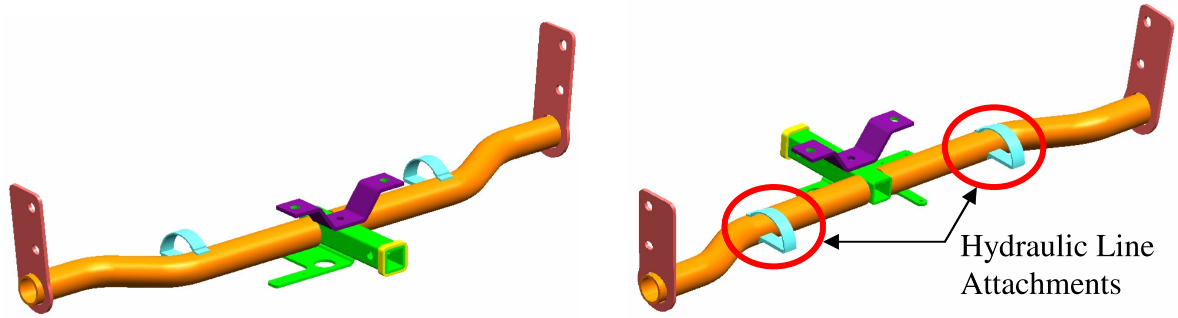

Figure 17: View of alpha design CAD model from rear of vehicle (left) and front of vehicle (right)

The hydraulic line attachments are indicated in Figure 17 above. All other components would be part of the stock trailer hitch manufactured by GM. A larger view of the hydraulic line attachment is shown in Figure 18. The larger cylinder represents a cross-sectional piece of the trailer hitch and the smaller cylinder represents a cross-sectional piece of the hydraulic line. Determination of the exact number and locations of the fluid line support mechanisms would have required further engineering analysis and was not determined for the alpha design.

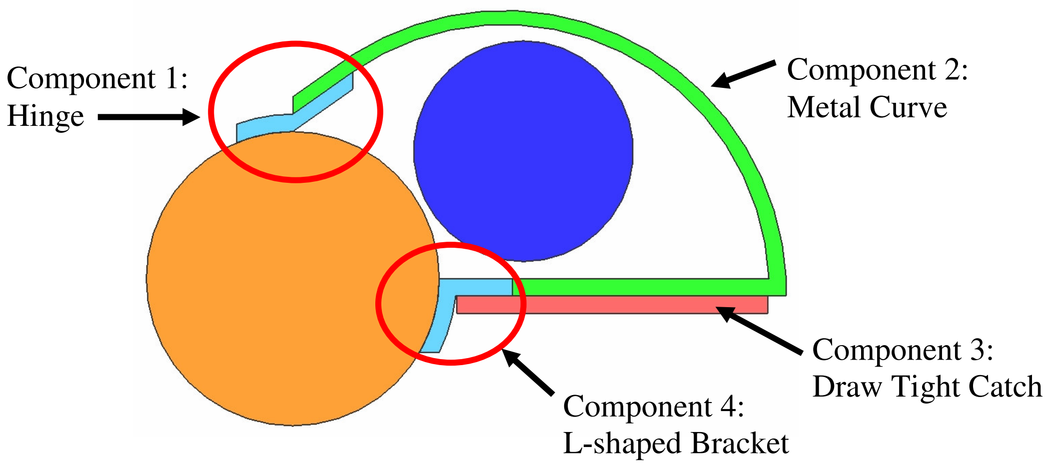

Figure 18: Hydraulic line support mechanism design

The hydraulic line support mechanism consisted of four components, as highlighted in Figure 18 above. The first component was a small, metal hinge welded directly to the trailer hitch, which would allow the support mechanism to pivot open and closed around the hydraulic lines. This metal hinge is shown in Figure 19.

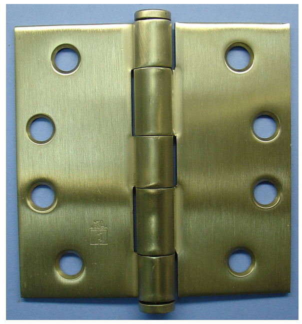

Figure 19: Metal hinge for fluid line support mechanism

Component 2 was a bent metal curve that would have been welded to the metal hinge (component 1), wrapped around the hydraulic line, and bent into a flat section for a draw tight catch to be attached (component 3). The metal curve would also have been coated with rubber to prevent any sharp, exposed metal from damaging the hydraulic line, and also to prevent corrosion.

A draw tight catch, similar to the one shown in Figure 20, would be used to secure the bent metal curve (component 2) to the trailer hitch. This catch would be made up of two parts. The larger part, as pointed out, would act as a handle and would be welded to the flat part of the bent metal curve. The smaller part, the hook, would be attached to an L-shaped plate (component 4), which would be welded directly to the trailer hitch.

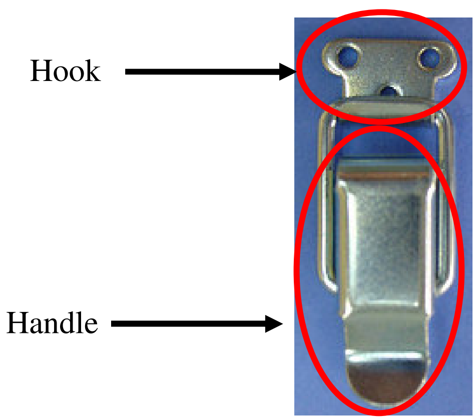

Figure 20: Draw tight catch for fluid line support mechanism

As shown in Figure 18, the L-shaped plate (component 4) would provide a connection between the draw tight catch and the tubing of the trailer hitch. This component would allow the draw tight catch to remain on a flat surface as necessary for an accurate connection.

6.2 Prototype

One of our main focuses in critically assessing our alpha design was to develop an alternative to welding the hydraulic line attachment directly to the trailer hitch. We wanted to eliminate this welding for three reasons: (i) we were concerned that welding onto the trailer hitch would decrease the structural integrity of the hitch, (ii) the paint coating on the stock trailer hitch would make it very difficult to weld the hydraulic line attachments onto the main bar of the hitch, and (iii) we wanted to create a design that would not require a Challenge X competition waiver. Therefore, our prototype design concept featured a stock GM trailer hitch with hydraulic line attachments that wrapped around the circular cross section of the trailer hitch, instead of welding onto the hitch.

Additionally, we eliminated the draw tight catch (Component 3 in Figure 18) to make the design simpler and easier to manufacture. One of our main concerns was that we would not be able to weld the draw tight catch onto the curved bar (Component 2 in Figure 18) or L-bracket (Component 4 in Figure 18) because the catch had a brass finish. Also, we would have been unable to connect these components with bolts due to the limited amount of material on the catch, which made it infeasible to drill a bolt hole.

Figure 21 shows a three-dimensional CAD rendering of the prototype and also a picture of our fabricated prototype.

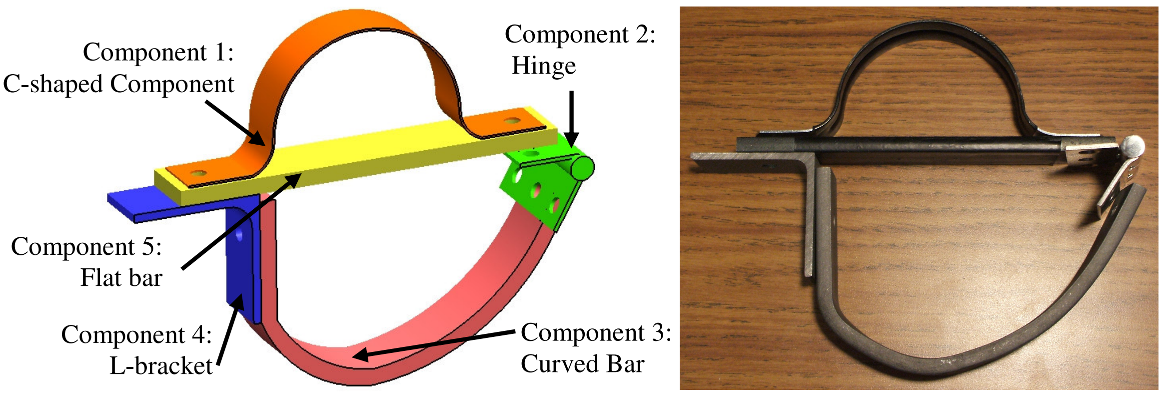

Figure 21: 3-D rendering (left) and manufactured (right) prototype

Our prototype used 0.25 inch thick steel for the curved bar and the flat bar and featured an L-bracket that was bolted to the curved bar. This L-bracket was longer in length than the flat bar, as shown in Figure 21. Additionally, the C-shaped component, flat bar, and curved bar were covered with a rubber coating.

We manufactured a prototype of our hydraulic line attachment mechanism to prove the most important elements of our final design. First, we validated the geometry of the hydraulic line attachment relative to the vehicle. By installing the prototype into the vehicle, we verified that each piece of the hydraulic line attachment fit into the vehicle without geometric or clearance issues, except the L-bracket, which was modified for the final design. We used the prototype to show that the design supports the hydraulic line, neither allowing the line to sag, nor pulling the line up farther that it was able to deflect. Second, our prototype proved the motion of the mechanism. We were able to assemble the pieces together and swing the curved bar through the motion of the hinge. We were also able to physically verify that the motion of the hinge was not disrupted by the location of the hydraulic line when the prototype was installed in the vehicle.

7 CONCEPT DESCRIPTION

Our final design concept for the U of M Challenge X Team's trailer hitch is shown in the 3D CAD model in Figure 22. It is composed of a stock trailer hitch purchased from GM and two hydraulic line attachments fabricated by our team.

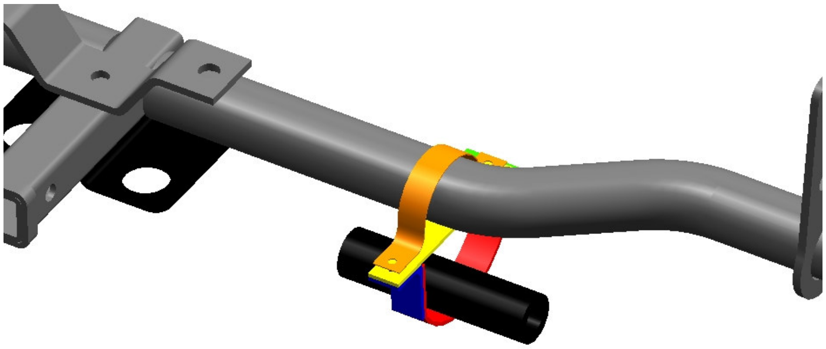

Figure 22: 3D CAD model of final design concept

Each hydraulic line attachment consists of five components, as shown in Figure 23.

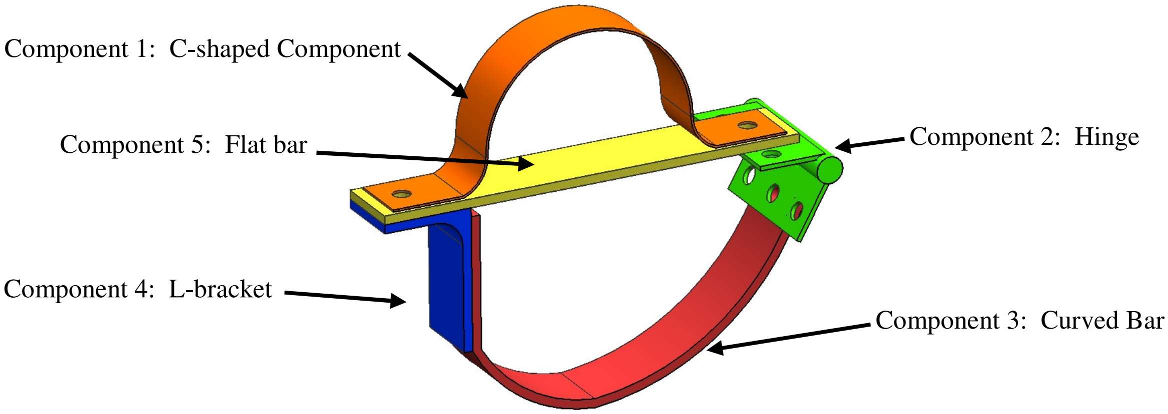

Figure 23: CAD model of hydraulic line attachment

The first component is a C-shaped component that wraps around the cross-section of the trailer hitch and connects to a flat bar to hold the entire mechanism in place. One end of this flat bar is connected to the pre-manufactured hinge, which allows a curved bar to swing around the hydraulic line for easy installation. The other end of this curved bar is connected to an L-bracket, which allows the curved bar to bolt back up to the flat bar, thereby securing the hydraulic line in place underneath the trailer hitch. Figure 24 outlines this two stage operation for fastening a hydraulic line with the support mechanism, while the entire mechanism remains attached to the trailer hitch.

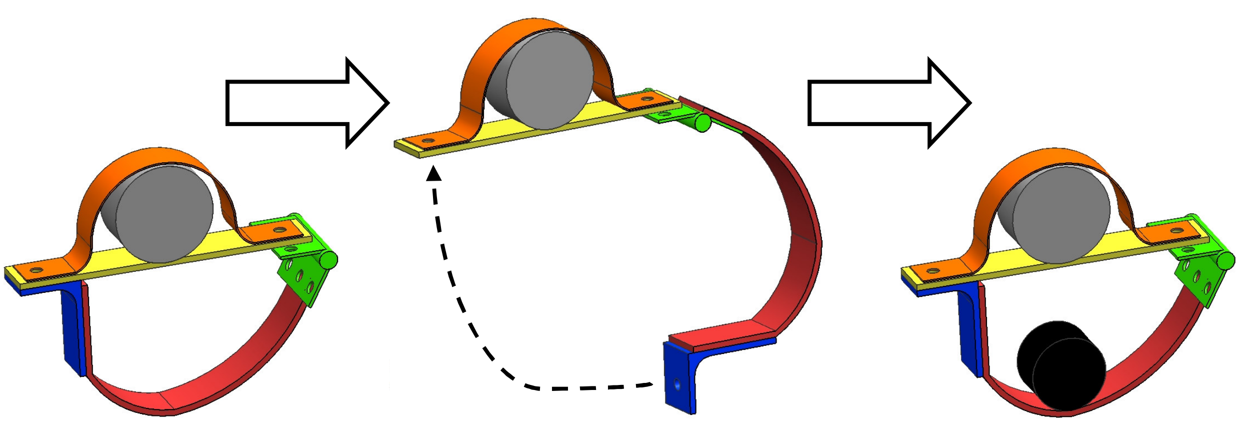

Figure 24: Operation of final design concept

Once installed, the hydraulic line support mechanism will remain fixed around the trailer hitch. Figure 25 conveys how the various components of the hydraulic line support mechanism fit together to form an entire mechanism that can be attached to the trailer hitch.

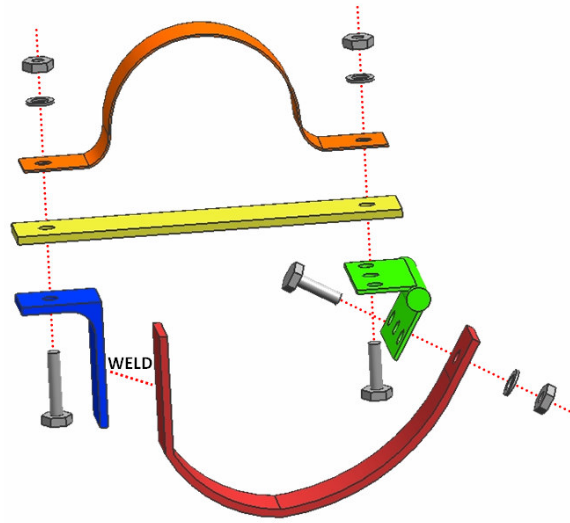

Figure 25: Layout drawing showing the interaction between components in the final design concept

Two bolts, one placed through the C-shaped component, flat bar, and hinge and one placed through the C-shaped component, flat bar, and L-bracket, will secure the support mechanism around the trailer hitch. The bolt through the L-bracket will need to be removed and refastened each time a hydraulic line is to be placed in or removed from the mechanism. Additionally, a bolt will be placed through the hinge and curved bar to keep these components fixed together.

8 PARAMETER ANALYSIS

This section describes the methods and engineering decisions used to develop the details of our final design.

8.1 Determination of Hydraulic Line Attachment Design

To determine the specific parameters for our design, we used the following approach. The first step was to find a pre-manufactured C-shaped component, (the pipe strap shown in Figure 26), that fit around the circular cross-section of the trailer hitch. Since this component already had bolt holes drilled into its flanges, we decided to keep this dimension for the distance between bolt hole centerlines. There were also other choices for a pre-manufactured pipe strap that had the same thickness as our chosen pipe strap, but were smaller in diameter and would not fit around the trailer hitch. Our search for additional choices was unfruitful.

Figure 26: C-shaped component

We also found pre-manufactured stainless steel hinges, shown in Figure 27, to use in our design. The width of the pipe strap was 0.875 in, so we wanted to use the small hinge, whose 1 in width would be close to that of the pipe strap. We also wanted to drill bolt holes through the wings of the hinge, however, we were unable to do this because of the small hinge's short length. Therefore, we had to use the larger hinge, which was 2 in wide.

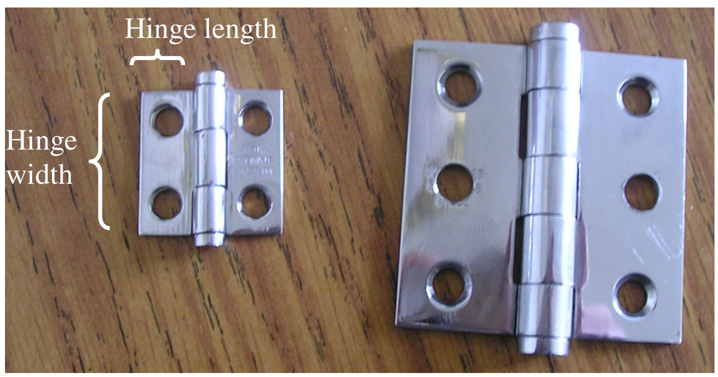

Figure 27: Small and large hinges considered for hydraulic line attachment

For the L-bracket, we were able to purchase 0.125 in thick L-stock, which we then cut and drilled to our specifications. For the bolt hole, we left 0.75 in clearance between the hole centerline and the outer face of the 90º angle of the L-bracket, to allow for ease of bolt installation.

The next component we analyzed was the curved bar. The shape of this bar was determined based on: (i) the minimum required distance between the trailer hitch and the hydraulic line, (ii) geometry constraints due to the hinge and L-bracket, and (iii) maximizing the radius of curvature to make the bar easier to bend in the manufacturing process.

For our prototype design, we used 0.25 in thick steel. However, to reduce weight and cost, we investigated the feasibility of using steel that was half as thick. To perform our analysis, we modeled the curved bar in a FEA software, HyperMesh. We imported the curve shape as a .dxf file from our AutoCAD2008 model and, after creating top and bottom surfaces from the geometry of the model, we created a midsurface along the length of the curved bar. Next, we meshed our model along this midsurface, with refined circular meshes at the locations of the bolt heads, using a PSHELL property collector for steel ($E=30x10^6$ psi, NU=0.29) with a 0.125 in thickness. We also applied constraints (6 degrees of freedom) to the nodes at the bolt head locations.

From our AutoCAD file, we were also able to import the cross-section of the hydraulic line relative to the curved bar. We used the outline of the hydraulic line to determine which elements of the curved bar would be in contact with the hydraulic line. Then, we applied a downward force of 15 lbs to these elements. This force was determined by calculating the downward force, F , due to the hydraulic lines and the hydraulic fluid and multiplying by a factor safety of about 3. The calculation for force, F, is shown in Eq. (1), where W_{line} is the mass per unit length of the hydraulic line, L is the length of the hydraulic line, ρ is the density of the hydraulic fluid in pounds per volume, g is the acceleration due to gravity, and V is the volume of hydraulic fluid contained in the length of hydraulic line.

$$F = W_{line} L + \rho V g = (1.48 lb / ft) \cdot (3 ft) + (1.73 slugs / ft^3)(0.0164 ft^3)(32.2 ft / s^2) = 5.4 lb \qquad (1)$$

After running the HyperMesh solver and obtaining deformation and stress results for our initial mesh, we split the mesh and ran the HyperMesh solver again to verify mesh independence. This resulted in less than 2.5% difference between the deformation in the coarse and fine meshes, showing sufficient convergence and increasing our confidence in the FEA results. The stress results for our fine mesh are shown in Figure 28 below. Further details are shown in Appendix E.

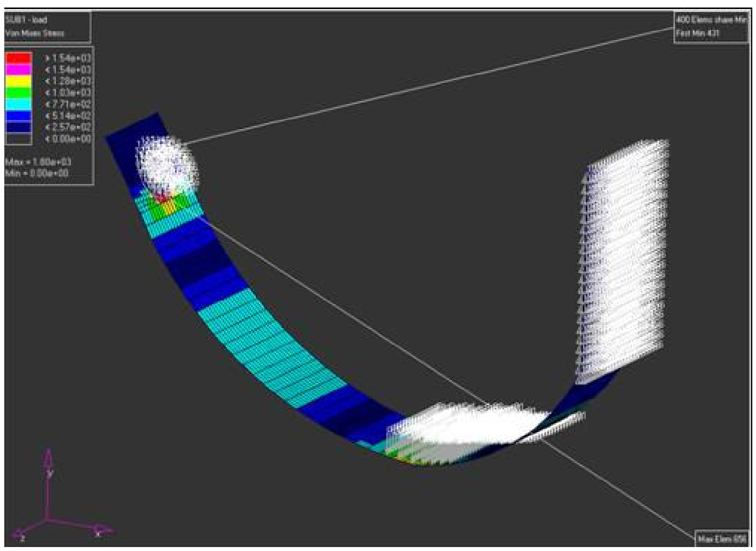

Figure 28: HyperMesh stress results for curved bar with 0.125 inch thickness

As indicated in Figure 28, the maximum stress of 2.0 ksi occurs underneath the bolt hole on the straight vertical section of the bar. Since this stress is much less than 50 ksi (the material yield strength of the steel we used), our analysis indicated that the 0.125 inch thick steel would not experience failure due to yield, thereby validating our design change for reducing material thickness in the curved bar.

We also considered using aluminum in our design. However, we were initially planning to use a manufacturing process that included significant amounts of welding, specifically welds directly between our manufactured components and the steel trailer hitch. This welding would require the materials to be compatible. Also, commonly available aluminums have yield strengths much lower than 50 ksi and steel is lower in cost than aluminum. Therefore, we decided to use steel for our manufactured components.

The next component that we designed was the flat piece between the trailer hitch and the hydraulic line. The purpose of this component was to secure the entire mechanism onto the trailer hitch and to protect the hydraulic line from rubbing against the metal of the trailer hitch. Since the flat piece was not a major load-bearing component, we decided to use the same 0.125 in thick steel that we used for the curved bar.

To prevent wear due to corrosion, metal-to-metal contact, and direct metal contact with the hydraulic line, we tested two setups for applying a preventative material or coating to the C-shaped component, the flat piece, and the curved bar. First, we considered using a thick, silicone material and affixing it to the metal components with epoxy. Upon testing, however, we found that the silicone easily peeled off of the epoxy layer, which was unacceptable. For our second setup, we tested a multi-purpose rubber coating that was applied to the components through dipping. This coating was easy to apply and adhered to the steel pieces very well. Therefore, we decided to use the rubber coating for our protective layer.

8.2 Determination of Number and Location of Hydraulic Line Attachments

After finalizing our hydraulic line attachment design, we used beam bending theory to determine the number of attachments required to support the hydraulic line. The equation for the stiffness of a beam is given by Eq. (2) below, where k is the stiffness of the beam, P is the load at the midspan of the beam, and δ is the deflection at the midspan of the beam [16].

$$k = \frac{P}{\delta} \tag{2}$$

Then, the natural frequency of a beam was calculated by Eq. (3), where f is the natural frequency of the beam, in Hz, and m is the mass of the beam [16].

$$f = \frac{1}{2\pi} \cdot \sqrt{\frac{k}{m}} \tag{3}$$

We used this theory for a simple physical test to determine the stiffness of the hydraulic line, and then we calculated the resonant frequency of the hydraulic line for a given length between supports. This natural frequency was compared to the vehicle frequency criterion of 25 Hz. This criterion was determined based on discussion with a Noise and Vibration engineer from GM. (See Section 16.10 for further details).

After determining the necessary spacing of the hydraulic line attachments, we optimized the locations of the hydraulic line attachments in terms of the trailer hitch. To do this we used FEA to determine the areas of high stress concentration on the main bar of the hitch, so we could avoid these areas when placing our hydraulic line attachments. To do this, we imported the trailer hitch surfaces into HyperMesh, created midsurfaces, and then created PSHELL components with the material properties of steel and the thickness of the trailer hitch. We simulated welding by equivalencing the nodes of connected pieces. We constrained the trailer hitch with six degrees of freedom on the nodes that represent the area of the bolt heads, and we applied a force of 3500 lbs to the rearward hemisphere of the cotter pin holes, which transfers the load of the trailer to the trailer hitch. We used the HyperMesh solver to generate the stress results shown in Figure 29 and found that the areas of high stress were located in the middle bracket, not along the main bar.

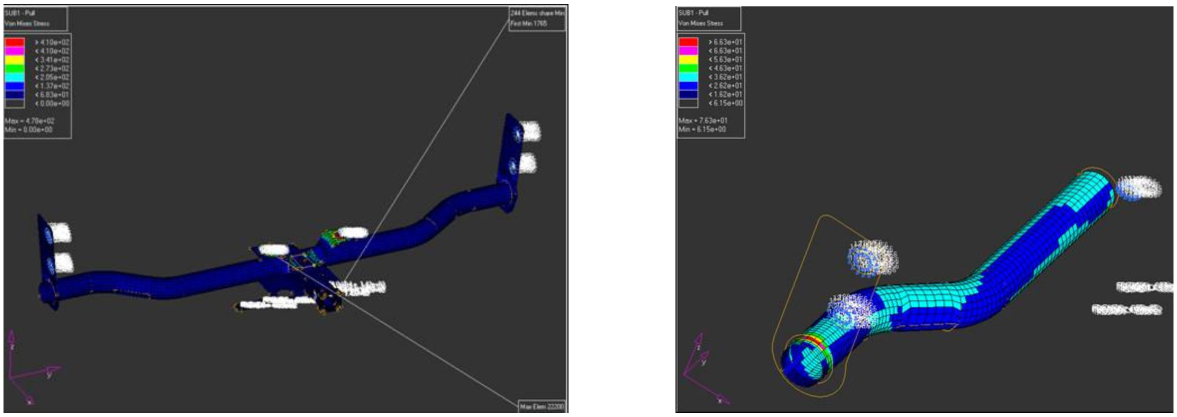

Figure 29: FEA stress results for entire stock trailer hitch (left) and main bar only (right)

Therefore, the placement of the hydraulic line attachments along the bar was not significantly dependent on the stress contours in the bar. Thus, the locations were mainly based on geometrical constraints due to the locations of other components in the vehicle.

8.3 Results from Analyses Assignments

In addition to the methods we used to develop our final design, our team also completed the following analyses to supplement our project.

8.3.1 Material Selection

For our first material selection, we analyzed materials for the six major load-bearing components. We determined that the best materials would maximize strength and stiffness while minimizing weight and material cost. Using the *CES EduPack 2007* software, we determined that the best material to use was AISI 1030 carbon steel, which was the cheapest of the top five materials and had comparable corrosion resistance.

For our second material selection, we analyzed materials for the coating applied to the hydraulic line attachments. The function of this coating was to maximize corrosion resistance while minimizing cost and weight. Using the *CES EduPack 2007* software, we determined that the best material to use was butyl rubber. Of our top choices, the butyl rubber was most resistant to salt water corrosion and had comparable corrosion resistance for fresh water, weak acids, strong acids, weak alkalis, strong alkalis, organic solvents, and UV radiation. Additionally, butyl rubber is typically use in car tires, so it is likely that GM would have some familiarity with this material. Further details are provided in Appendix I.

8.3.2 Manufacturing Process Selection

Since hydraulic hybrid technology is a relatively new development, hydraulic hybrid vehicles would initially make up only a small percentage of vehicles produced by automotive companies. Therefore, our target production is 1000 hydraulic line attachments. Based on our analysis in the CES Manufacturing Process Selector, for the AISI 1030 carbon steel components we would use a sheet stamping manufacturing, with a combination of bending and stretching processes to form one unit. This process would allow for the unique shapes and holes in our components, especially those in the curved bar design. Our analysis indicated that the capital write-off time for this process would be 5 years.

We also analyzed the manufacturing process for the butyl rubber and determined that the best manufacturing process would be to use water-based painting application as a surface treatment process. For this process, the relative equipment cost is medium, tooling cost is low, and the time before handling is 500-5000 seconds. Additionally, this manufacturing process gives good weathering resistance, thereby satisfying our need for corrosion resistance. These analyses are explained further in Appendix I.

8.3.3 Design for Assembly

We used the Boothroyd-Dewhurst method to analyze the design efficiency of our prototype design and found the design efficiency to be 38.5%. Then, based on our test for minimum number of parts, we decided to weld the L-bracket and curved bar together, thereby eliminating the bolt between these two components, which, from an assembly standpoint, essentially combined these two parts into one integral component. We were also able to improve the assembly process by assembling the components in a different order. Starting the assembly process with the bolt between the hinge, flat bar, and C-shaped component allows the bolt holes of these components to be aligned, which reduces insertion time. Therefore, the design efficiency of our final design was increased to 51.9%. Further details are given in Appendix I.

8.3.4 Design for Environmental Sustainability

We completed a Design for Environmental Sustainability analysis using SimaPro. We analyzed C55 I steel and EPDM rubber ETH U materials similar to those determined from our Material Selection analysis, carbon steel and butyl rubber, respectively. We found that the C55 I steel had a greater mass air emissions, raw material usage, and (solid) waste, while the EPDM rubber ETH U had greater water emissions. The C55 I steel has a greater impact on minerals, land use, acidification/eutrophication, ecotoxicity, climate change, and respiratory inorganics, while the EPDM rubber ETH U has a greater impact on ozone layer, radiation, respiratory organics, and carcinogens. Based on the normalized score in human health, eco-toxicity, and resource categories, resources was likely to be the most important category from the analysis of C55 I steel. For the EPDM rubber ETH U, human health had a slightly greater normalized score than resources, and the score for Ecosystem Quality was the lowest damage meta-category for both materials. Finally, the EcoIndicator 99 “point value” for C55 I was 23, while the “point value” for EPDM rubber ETH U was only about 4. This indicated that the C55 I steel would have a larger impact when considering the life cycle of the whole product. Therefore, based on our analysis, the steel in our design will have a greater environmental impact, both on its own and from a life cycle analysis standpoint, than the impact caused by the rubber. See Appendix I for further details.

8.3.5 Design for Safety

We used the DesignSafe program to assess the risks associated with our project. The greatest risk would be caused if there are sharp edges on the hydraulic line attachment. These edges could puncturing the hydraulic line and cause hydraulic fluid to leak. This would hinder vehicle operation, cause hazards to the user, and harm the environment. As a result of this analysis, we rounded all sharp edges on the components of our final, manufactured hydraulic line attachments to prevent these problems from occurring. Further details are given in Appendix I.

9 FINAL DESIGN

Our final design, shown in Figure 30, is comprised of two main parts: the stock GM trailer hitch and two hydraulic line attachments, placed in optimized locations on the main bar of the trailer hitch. Figure 31 shows one of these hydraulic line attachments manufactured by our team.

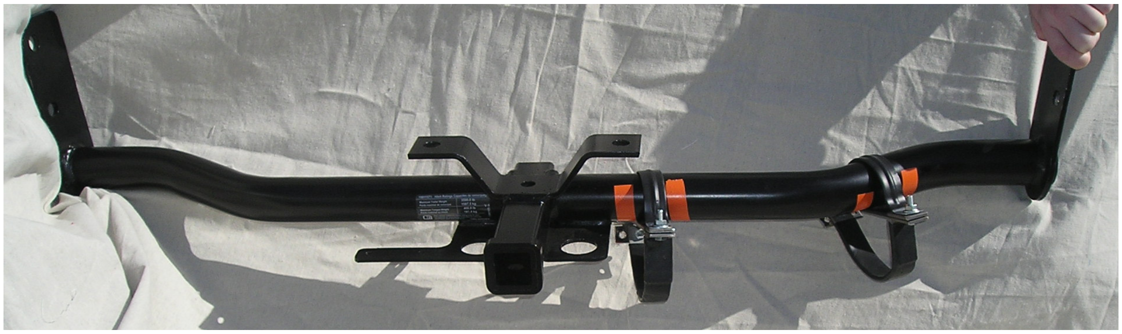

Figure 30: Photograph of final design

Figure 31: Manufactured hydraulic line attachment

Table 3 below lists the major components in our design. A full list of all components is given in the Bill of Materials shown in Appendix F.

Part #	Part Name
1	Stock trailer hitch
2	C-shaped component
3	Hinge
4	L-bracket
5	Curved bar
6	Flat bar

Table 3: Major parts list for final design

The first major component in our final design is a stock trailer hitch for a Chevy Equinox, provided by GM. This pre-manufactured part is available through *GM Parts Direct* (catalog number 19169825).

The second component of the final design is the C-shaped component, shown as an engineering drawing in Figure 32. This component is a pre-manufactured pipe strap made of stainless steel. It is rubber-coated to avoid metal-on-metal contact between the trailer hitch and the pipe strap, thereby inhibiting abrasive wear. This coating also creates a snug fit between the components, which will prevent slip.

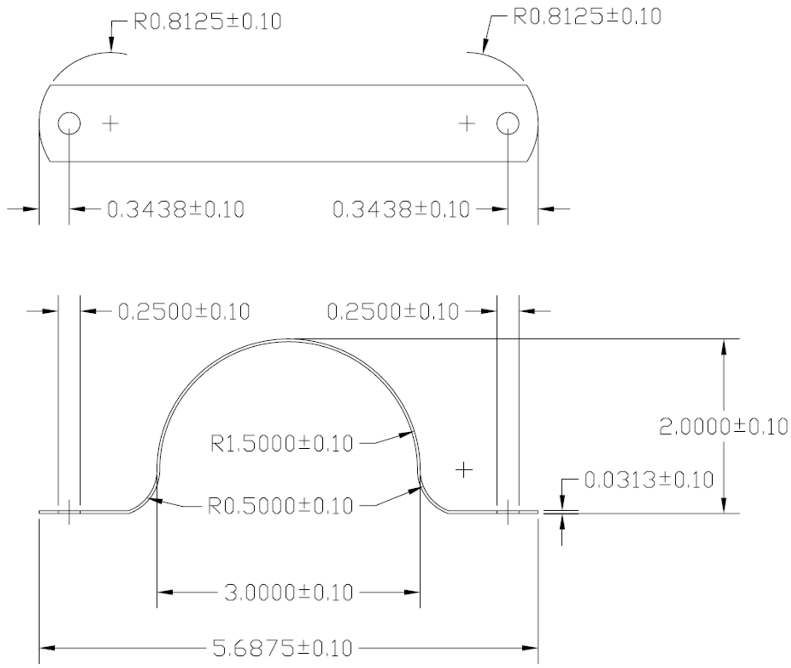

Figure 32: Dimensioned, 2D views of the C-shaped component

The third component of the final design is the flat bar, as shown as an engineering drawing in Figure 33. This component is made of A-36, hot-rolled steel and is also rubber-coated to prevent metal-on-metal contact with the trailer hitch. This rubber coating provides a protective layer between the metal of the flat bar and the hydraulic line, and also prevents corrosion of the flat bar.

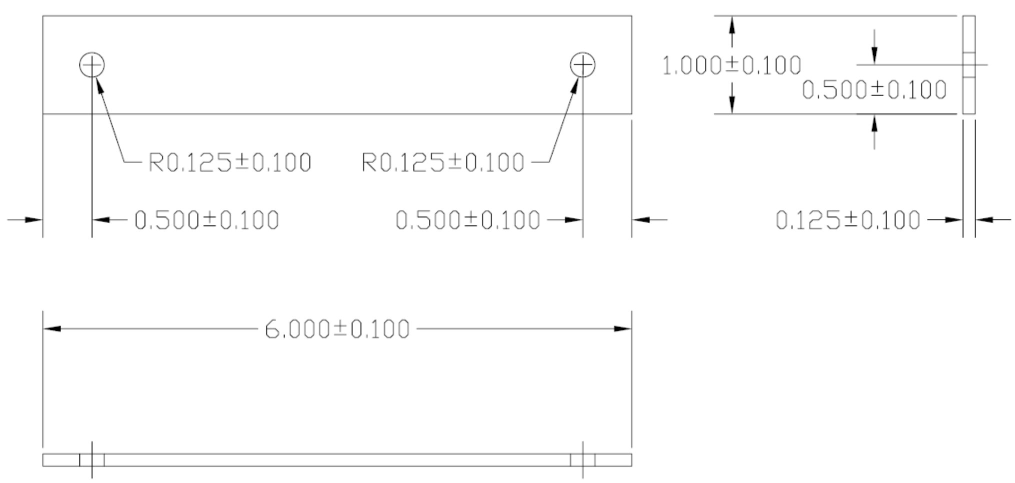

Figure 33: Dimensioned, 2D views of the flat bar

The fourth component of the final design is the pre-manufactured, stainless-steel hinge, shown as an engineering drawing in Figure 34. This component facilitates the motion of the mechanism to swing open and closed around the hydraulic line, thereby enabling hydraulic line readjustment.

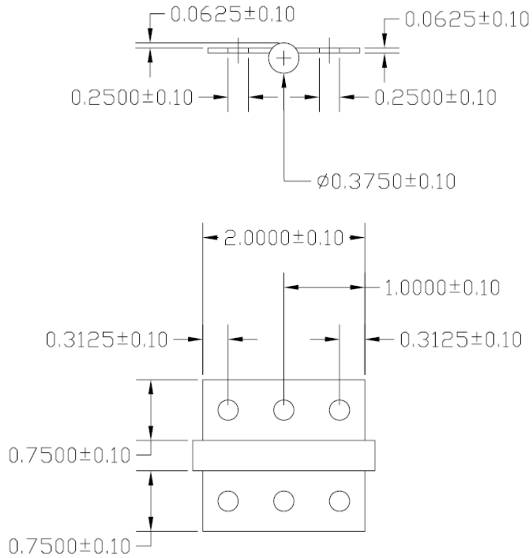

Figure 34: Dimensioned, 2D views of the hinge

The fifth component of the final design is the curved bar, shown as an engineering drawing in Figure 35. This bar is designed as a custom curve to align with the hinge and L-bracket and to support the hydraulic line at its closest distance to the trailer hitch. It is made of the same A-36, hot-rolled steel as the flat bar and is also rubber coated to prevent the metal from rubbing through the surface of the hydraulic line and to inhibit corrosion of the curved bar.

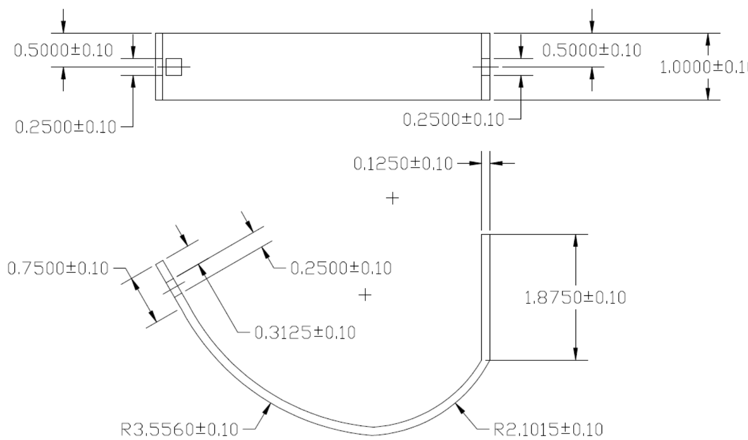

Figure 35: Dimensioned, 2D views of the curved bar

The sixth, and final, major component of the final design is the L-bracket, shown in Figure 36. This bracket is welded to the curved bar and serves as the bolted interface between the curved bar and the flat bar, which meet at a right angle.

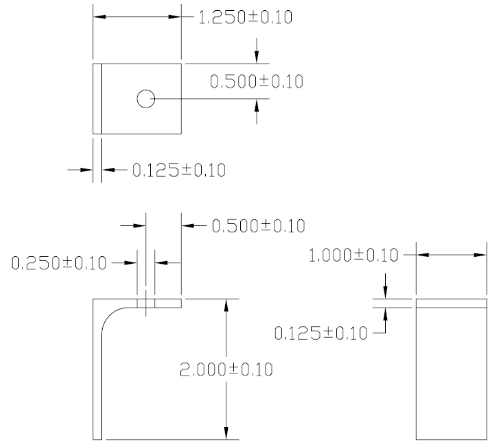

Figure 36: Dimensioned, 2D views of the L-bracket

The end goal of this project was to create a working model that the U of M Challenge X Team could use in the May 2008 Road Rally, therefore, there are no deviations between the final design presented here and the final manufactured product. The operation of this final design was discussed in detail in Section 7 and all validations for the design will be discussed in Section 11.

10 FABRICATION PLAN

We fabricated a prototype as an intermediate, proof-of-concept step in developing our final design. We also manufactured our final design. One final hydraulic line attachment was used for validation testing and two others were incorporated into our working model. The sections below state the fabrication process for both the prototype and the final design, and also address critical tolerances in these plans.

10.1 Prototype Fabrication

Figure 37 shows a cross-sectional view of the prototype that our team fabricated in the ME 450 machine shop facilities.

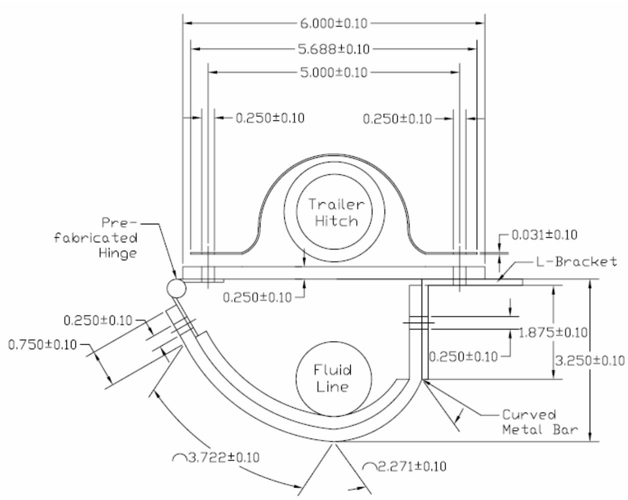

Figure 37: Dimensioned drawing of the hydraulic line attachment prototype

The most difficult component to manufacture was the curved bar. In order to accurately manufacture this component, our team used the following bending procedure. First, we created a template by printing our CAD drawing to scale, and then cut out the paper pattern. We glued this pattern onto a 7 in × 5 in × 1 in piece of aluminum, and then used the band saw and circular sander to cut and smooth the metal into our desired curve. Once the aluminum template was completed, a blow-torch was used to heat the 24 in × 1 in × 0.25 in bar beyond its critical temperature. Since we used hot-rolled steel, we were able to form the bar around the template into the correct shape. Once the curved bar was cool, our team drilled 0.25 in diameter holes into the ends of the curved bar.

The next step in the manufacturing process was to cut straight steel stock into two 6 in ×1 in × 0.25 in bars using the band saw to create the flat bar components. Then, we used the drill press to drill 0.25 in diameter holes into these straight bars, as well as the stainless steel hinges and the L-brackets.

Finally, we covered the bolt holes of the C-shaped component, straight bar, and curved bar with Scotch tape and dipped the pieces in rubber coating. We applied three layers, allowed the coating to dry completely, and then removed the taped areas with a knife.

For the fasteners in our prototype, we used a single one-inch, 0.25 in diameter bolt with 20 threads per inch, along with a matching hex nut, to align and attach the corresponding bolt holes in the L-bracket, the flat bar, and the C-shaped component. For the other three bolted connections, we used 0.75 in long, 0.25 in diameter bolts with 20 threads per inch and matching hex nuts.

10.2 Final Design Fabrication

The fabrication process of the final design remained the same as the prototype, except for the following changes:

- The thickness of curved bar and flat bar components was 0.125 in instead of 0.25 in.
- The length on one side of the L-bracket was shortened with a bandsaw to be flush with the corresponding edge of the flat bar.
- The L-bracket was connected to the curved bar via TIG welding instead of a bolt.
- All bolts used were 0.25 inch diameter and 20 threads per bolt length of 0.75 inch, with matching hex nuts, which was possible due to the decreased thickness of the flat bar.

The entire manufacturing process for our working model is summarized in Table 4 below.

Component	Machine	Detailed Description
C-Shaped	None	1. Dip in rubber coating
Flat Bar	Bandsaw Drill press	1. Cut 6 inch piece of 0.125 in thick A-36, hot-rolled steel 2. Drill two 0.25 in diameter holes 5 in center-to-center
Stainless Steel Hinge	Drill Press	1. Drill two 0.25 in diameter holes
Curved Metal Bar	Bandsaw Bandsaw Blow Torch Drill press	1. Cut aluminum template pattern of curved metal bar 2. Cut 12 in piece of 0.125 in thick A-36, hot-rolled steel 3. Form A-36, hot-rolled steel around metal template 4. Drill two 0.25 in diameter holes in A-36, hot-rolled steel
L-Bracket	Drill press Bandsaw Welding	1. Drill one 0.25 in diameter hole 2. Cut L-bracket 3. Weld L-bracket to curved bar using TIG welding

Table 4: Manufacturing plan for final design

10.3 Critical Components and Tolerances

The critical tolerance in our prototype and final design is the 5.00 ± 0.1 in distance between bolt centerlines in the C-shaped component and the flat bar as shown in Figure 38. This tolerance is critical because if there is much variation, these bolt holes may not line up with the holes in the hinge and L-bracket. This would prevent the entire mechanism from being able to bolt closed.

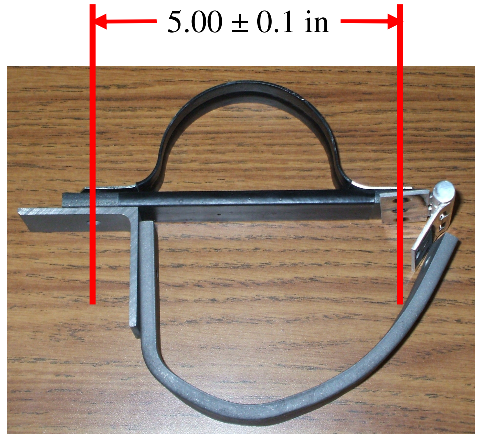

Figure 38: Critical alignment of bolt holes

The other critical tolerances in our design are the radii in the curved bar. Due to the nature of the manufacturing process for bending steel stock into our curved bar, it is difficult to keep close tolerances in this component. This could also cause difficulties in making the bolt holes line up correctly. The least critical tolerance in our design is the weld between the L-bracket and the curved bar. As long as these components are securely affixed together, the weld is sufficient.

11 VALIDATION RESULTS

To prove that our design meets all of our customer needs, we have taken each engineering specification from our QFD diagram (shown in Figure 10) and determined a validation approach. Table 5 outlines these approaches.

Rank	Engineering Specification	Validation Method
1	Trailering capacity	GM-validated
2	Number of bolts required for attachment	Uses 6 bolts
3	Clearance between bumper and trailer hitch	Measure clearance after installation
4	Clearance between oil cooler and trailer hitch	Measure clearance after installation
5	Designed as SAE Class II towing hitch	GM-validated
6	Mass reduction during corrosion testing	Chemical testing
7	Trailer hitch weight	Measure weight
7	Working model tested and verified by April 10	Completion for Design Expo
9	Procurement, material, and testing costs	Expenditure does not exceed $400
10	Number of points attaching fluid line to trailer hitch	Physical Testing/Vibrational Analysis
10	Sustains live load	FEA
12	Material yield strength	Material property check
13	Zero circuit malfunctions during testing	Electrical component test
14	Steps in manufacturing process	Fabrication Plan

Table 5: Methods for validating engineering specifications

As indicated, several of the engineering specifications did not require validation testing because we assumed that the analysis had already been completed by GM. By using the stock trailer hitch, we did not modify any of the structural components of the trailer hitch. Therefore, we assumed that the validations for trailer capacity, SAE Class II towing hitch, and yield strength criteria for the trailer hitch material were already successfully completed. Also, by using the stock trailer hitch, the six-bolt attachment between the trailer hitch and the vehicle was inherent in our design, and therefore, this specification did not need to be validated.

The clearance requirements were validated when we installed our final working model into the U of M Challenge X Team's vehicle. We did not find any interference between our working model and nearby vehicle components (see Figures 1 and 2).

To determine the weight of the final trailer hitch, we used a standard scale to weigh the entire trailer hitch with the hydraulic line attachments affixed. The entire final design weighed 28.3 lbs. Though this value is slightly greater than our target weight of 27 lbs, this minimal weight increase was acceptable when compared to the overall weight of the vehicle.

By building the April 10th deadline into our critical path, we completed all manufacturing and analysis of our working model in time for the Design Expo.

Also, by keeping track of our expenses and considering cost in all of our decisions, we did not exceed our $400 budget. The total expenditure for our project was $196.33. The main components of this cost were validation testing supplies and materials for manufacturing the hydraulic line attachments. The stock trailer hitch was supplied through U of M Challenge X Team funding.

The requirement for determining the number and spacing of hydraulic line attachments was determined through physical testing. We wanted the distance between attachments to be small for two reasons: (i) so the lines would not deflect and hit the trailer hitch, and (ii) so the lines were not able to reach their resonant frequency, which could cause Noise, Vibration, and Harshness (NVH) issues in the vehicle. However, for cost and weight considerations, we also wanted to minimize the number of attachments required. We used the beam bending theory discussed in Section 8.2 for our physical testing. To determine the stiffness of the hydraulic line, we clamped a 3 ft. long piece of hydraulic line between two C-Clamps obtained from the ME 450 Machine Shop, as shown in Figure 39.

Figure 39: Pull test setup to measure deflection of hydraulic line

We started with a suspended length of 4 inches between the two C-Clamps. Then, we affixed a heavy duty zip-tie around the hydraulic line cross-section at the midpoint between the two clamped ends. Next, we hooked a force gauge onto the zip-tie and applied a lateral force of 15 lbs to the hydraulic line and measured the displacement of the hydraulic line at its midpoint. Using these measured values of applied force and resulting deflection in the equations described in Section 8.2, we calculated the stiffness and resonant frequency of the hydraulic line for a length of 4 inches. We continued increasing the suspended length in increments of 2 inches and determined the stiffness and resonant frequency at each measurement. Based on our discussion with engineers from GM, we needed to have a minimum resonant frequency of 25 Hz (See Section 16.10) and therefore, our test results indicated that the spacing between attachments needed to be less than 10 in (See Appendix G for full results). Also, as previously discussed, we created an FEA model of the entire stock trailer hitch and applied a 3500 lb trailering force. We found the stress in the middle bracket to be one magnitude greater than the stresses in the bar of the hitch. Therefore, the placements of the hydraulic line attachments along this bar were not significantly dependent on the stress contours in the bar. Thus, the locations were mainly based on geometrical constraints due to the locations of other components in the vehicle.

To check that our attachments were able to support a live load, we used FEA to look at the curved bar with a pressure force applied to simulate the weight of the line. Details of this analysis were described in Section 8.1, and supplemental information is provided in Appendix E. Our analysis indicated that approximately 330 lb of downward force would be required to reach the yield strength of the curved bar material. Since the weight of the hydraulic line was an order of magnitude smaller than this maximum force, we concluded that our design would sustain this live load.

One of our engineering specifications was for material yield strength to be less than or equal to 60 ksi. This criterion was set for the component bearing the trailering load, namely the stock trailer hitch. Since the GM hitch material had a yield strength of 60 ksi, it met this criterion. The steel used for the hydraulic line attachments had a yield strength of only 50 ksi. While this value was lower than our engineering specification, since the attachments did not support the trailering load, the requirement was not critical for the hydraulic line attachments.

To validate the electrical components of the trailer hitch, we purchased a 4-Wire Flat Tester, shown in Figure 40, which uses light-emitting diodes (LEDs) to show proper functioning of the taillight circuits. We plugged this device into the electrical box of the trailer hitch, turned on the power to the vehicle, and tested the turn signals and brake lights. This test proved that all electrical circuits functioned properly.

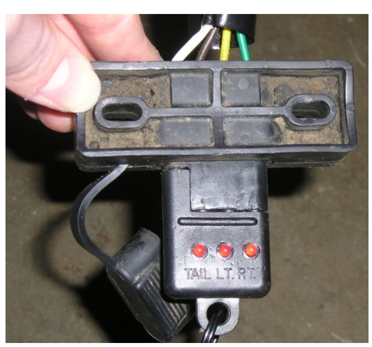

Figure 40: 4-Wire Flat Tester

We validated the corrosion requirement of less than 30% mass reduction via chemical testing. We submerged one hydraulic line attachment into a solution of 95% water and 5% road salt for a duration of four days. The mass of the specimen prior to testing was 412.9 grams. After testing was completed and the specimen, shown in Figure 41, was allowed to dry completely, the final mass was measured to be 420.9 grams, showing a 2% increase in mass. This increase was attributed to the excess salt that clung to the specimen. Additionally, after testing, we observed two cracks in the rubber coating. However, we attribute these cracks to the non-uniformity in the rubber coating and we believe a more uniform and consistent dipping process would eliminate the formation of such defects. Therefore, our design was validated for the corrosion requirement.

Figure 41: Corrosion tested hydraulic line attachment

Additionally, we conducted physical load testing to prove that the entire mechanism, specifically the C-shaped component, could withstand the loads induced by the hydraulic line. We simulated the trailer hitch with a steel tube of the same diameter and thickness. As shown in Figure 42, we clamped this tube on both ends and then attached our working model around the tube. We put a heavy duty zip-tie around the curved bar of our final design, and then used a force gauge to apply a 15 lb downward, vertical load. Next, we applied a 15 lb lateral load.

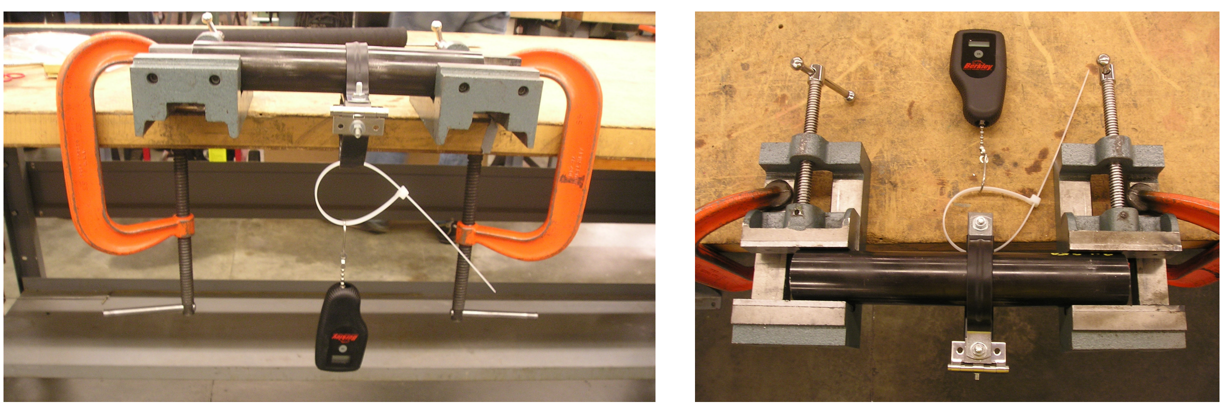

Figure 42: Vertical (left) and lateral (right) test setups to validate hydraulic line attachment

The criterion for this test was that the C-shaped component must not shear upon loading. Since we observed no deflection or failure upon testing, our design passed the inspection, validating our decision to use the pipe strap for our C-shaped component.

12 DISCUSSION

The following discussion is a critique of our design, along with lessons that we've learned from our project and also possible future modifications.

12.1 Strengths and Weaknesses

We have identified the three greatest strengths of our design. First, the hydraulic line attachments do not harm the trailer hitch because they wrap around the trailer hitch and have the protective rubber coating to prevent metal-to-metal contact. This gives the design high potential for obtaining a waiver from the Challenge X authorities. Second, the design allows the hydraulic lines to be attached or removed easily, without requiring the hydraulic line attachment mechanism to be fully removed from the trailer hitch. This was desirable to the U of M Challenge X Team because they will install the final trailer hitch design before they have completed their adjustments to the vehicle for competition. Third, our design is low cost. The cost of one hydraulic line attachment is $9.76, and the cost of the entire trailer hitch is $190.58.

We have also identified the three weakest aspects of our design. First, for the hydraulic line attachments, the rubber coating does not cover the entire mechanism. This allows the exposed steel to corrode more rapidly, and aesthetically, the abrupt end to the rubber coating is less desirable. Second, the design of the hydraulic line attachments has potential for lost bolts, especially during installation or hydraulic line adjustment. Third, by adding the hydraulic line attachments to the stock trailer hitch, we have increased the weight of the trailer hitch by 1.3 lbs. Although this is a small weight increase, it is still a negative impact of our design.

12.2 Lessons Learned

After completing our project, we have identified some of the lessons we learned by going through the entire development process. First, we found that our design problem changed as we moved further into the project, specifically, the changes in oil cooler location and the number of fluid lines that needed to be supported by our design. In effort to anticipate such changes, if we were to do the project again, we would spend more time on the problem-definition phase by asking more pointed questions up front to get a better idea of the problem and potential sponsor-defined changes that would affect our product.

Second, in hindsight, we would think more critically about what was needed from the end design. We developed our alpha design with the notion that welding the hydraulic line attachment to the trailer hitch would be a viable option. However, we later decided that this method of connection could decrease the structural integrity of the trailer hitch, which was undesirable and led to major changes between the alpha and final designs.

Third, we manufactured the hydraulic line attachments in batches. If we were to do the project again, we would determine our validation and optimization test methods earlier. This would allow us to determine the number of hydraulic line attachments we needed to make before we began fabrication in the ME Machine Shop. Manufacturing all at once would ultimately make our process more efficient.

As a final lesson learned, we would have improved our brainstorming session with our peers. In preparation for the session, we decomposed the trailer hitch design into specific focus areas, such as the middle bracket design, end bracket design, and attachment design. However, for a brainstorming session, this method of facilitation was too compartmentalized and hindered creativity. In retrospect, it would have been more effective to give a more general description of the desired outcome of the design and then allow our peers to be imaginative.

12.3 Possible Future Modifications

Our final design could be improved by making the following changes to the design and fabrication of the hydraulic line attachments. First, the design could be modified to have more than one point of contact between the hinge and adjacent components to prevent pivoting around the single bolt. This could be accomplished by using a custom hinge design with larger surface area or by using two smaller bolts. Also, the design would be more aesthetically pleasing if the length of the hinge was flush with the flat bar and curved bar, instead of extending out on both sides. Additionally, it would be important to tighten the tolerances, especially the critical tolerances on the curved bar and the flat bar (as discussed in Section 10.3) to ensure that the components fit together properly.

The design could also be improved by combining the curved bar and L-bracket into one component, to minimize parts and manufacturing steps. Furthermore, the process for dipping the components into the rubber coating could be improved by coating all exposed metal and by developing a way to ensure that the coating is uniform. This could include a more sophisticated method for drying the components after dipping, such as a rotating drying rack to prevent drips from drying permanently into shape. It would also be important to develop a better method for ventilation during the dipping process, such as a fan or a fume hood near the dipping area. Another possible modification would be to use an alternate coating for the hydraulic line attachments, such as the electronic coating used on the stock trailer hitch, which is applied as a liquid by dipping the component in tanks and then baking it to finalize the coating. In addition, using a thinner coating would allow all metal to be covered while meeting tolerances.

A further improvement could be made by making the device compliant. This could include replacing the hinge with a compliant mechanism, such as an accordion-shaped design to reduce part complexity, or using a snap-fit design in place of the bolt at the L-bracket that secures the curved bar around the hydraulic line.

13 RECOMMENDATIONS

Our team recommends that our working model be implemented in the U of M Challenge X Team's hydraulic hybrid Chevy Equinox to be used in the towing events in the Road Rally competition in May 2008. Our design can be used to tow trailering loads up to 3500 lbs, and is validated for the current hydraulic line installed in the vehicle. If a larger hydraulic line were to be used, we recommend additional validation testing, to be completed by applying vertical and horizontal forces on the hydraulic line attachments. Also, we recommend that the hydraulic line attachments be kept in the optimized locations on the trailer hitch to prevent any unsuspended length of hydraulic line from reaching resonant frequency, which could have a negative effect on the noise and vibration of the vehicle.

14 CONCLUSION

The University of Michigan Challenge X Team required a redesigned trailer hitch for their hydraulic hybrid Chevy Equinox to be able to tow a 3500 lb load, with the additional functionality of supporting the hydraulic line running underneath the vehicle. Our final design needed to be manufactured as a working model, validated by testing, and approved by a Challenge X waiver, to be used in towing events in the May 2008 Road Rally competition. Our team developed and fabricated a design that featured a stock trailer hitch purchased from GM with two uniquely-designed hydraulic line attachments. Our design was validated by numerous physical and computational analyses and is ready for use in the Challenge X Competition. At this point, we have submitted our design to Challenge X authorities and are awaiting feedback in regards to a competition waiver. If this feedback is delayed beyond the end of the semester, we will allow our sponsor to take over responsibility for finalizing the waiver.

15 ACKNOWLEDGEMENTS

We would like to thank our sponsor, the Challenge X Team at the University of Michigan, led by Javier Somoza, for their support, guidance, and ideas throughout the semester. Also, we would like to acknowledge Professor Gregory Hulbert for his continued support throughout our project. His help in the design and validation stages of this project were invaluable. Finally, we would like to thank Bob Coury of the ME Machine Shop. Bob's insight on various machining techniques was important during the fabrication of our project.

16 INFORMATION SOURCES AND REFERENCE LIST

Throughout the course of the project, our team gathered information from the following sources.

16.1 Hydraulic Hybrid Vehicles

The term "hydraulic hybrid vehicle" refers to a vehicle with a modified powertrain system that uses hydraulic fluid and a high-pressure pump to capture and use energy that would normally be lost as wasted heat due to braking friction in a conventional vehicle. Currently, the most practical type of hydraulic hybrid system is the hydraulic regenerative braking system. In this system, when the brakes are applied to slow the vehicle, energy from the wheels engage the hydraulic pump, which pumps hydraulic fluid into a storage tank containing nitrogen. The added fluid pressurizes the nitrogen, thereby storing energy. This energy is then used to force the hydraulic fluid back into the pump, causing it to act as a motor to power the wheels. In doing so, this hybrid system provides a means for improving fuel economy and reducing exhaust emissions [3, 4, 5].

The concept of the hydraulic hybrid vehicle is similar to that of a hybrid electric vehicle (HEV), in that both are powered by a gasoline or diesel internal combustion engine and also incorporate a system for storing energy. Hydraulic hybrids use hydraulic fluid and a pump, while electrical hybrids use electrical current and a generator. However, the applications for which these systems are better suited are different. Hybrid electric systems are best used in compact cars, while the hydraulic hybrid systems are more efficient for heavy-duty vehicles, such as SUVs, trucks, and, buses, which require more power and can more easily fit the large storage tanks. Also, the hydraulic hybrid system is more effective for stop-and-go traffic, which requires a lot of braking [5, 6]. In comparing the two systems, the hydraulic hybrid system is advantageous because it can store or disperse large amounts of energy in a short amount of time, while batteries cannot. Additionally, although the storage ability of today's batteries degrades over time, the energy storage ability of the hydraulic hybrid system does not. However, an electrical battery system can store more total energy than a hydraulic system [4]. More detailed information regarding hydraulic hybrid vehicle systems, such as design strategies and parallel versus series systems, is available but was beyond the scope of our trailer hitch design project.

16.2 Background Information on Trailer Hitches

In the most basic sense, a trailer hitch can be defined as, "a piece of steel that attaches to a vehicle frame to allow the vehicle to tow a trailer, use a bike rack, attach a cargo carrier, or use any other hitch mounted accessory" [7]. The Society of Automotive Engineers (SAE) has defined four classes of trailer hitches that are uniformly used as the industry standard within the United States based on the Gross Towed Weight Rating (GTWR), or the weight of the trailer and its cargo, and the trailer hitch receiver size. The receiver is the part of the trailer hitch into which the draw bar of the trailer or hitch accessory slides. The receiver size is the geometric dimensions of this rectangular opening. These classifications are listed in Table 6 [8].

Class	GTWR	Receiver Dimensions
I	< 2000 lbs	1¼" × 1¼"
II	2000 lbs – 3499 lbs	1¼" × 1¼"
III	3500 lbs – 4999 lbs	2" × 2"
IV	5000 lbs – 9999 lbs	2" × 2"

Table 6: Standard SAE trailer hitch classifications and associated receiver sizes

Almost all trailers and trailer hitch accessories are attached to the trailer hitch by a draw bar. These draw bars come in standard sizes dependent on the class of the trailer hitch and fit directly into the hitch's receiver. In some cases the draw bar, also known as a ball mount, has a round ball is attached to it. The connection between this ball and the object being towed serves as a ball and socket joint that allows for relative movement between the two objects [9]. This feature is particularly important when turning and towing over uneven road surfaces.

Another feature commonly used with trailer hitches is a weight distribution system, depicted in Figure 43.

Figure 43: Typical weight distribution system for trailer hitches

A weight distribution system is mounted into a trailer hitch and uses spring bars under tension to distribute part of the trailer's weight to the towing vehicle's front axle [7]. This type of system can greatly reduce the swaying and jerking of the trailer, thereby increasing the comfort of passengers in the towing vehicle.

16.3 Results of Patent Search

The original patent for a trailer hitch (Patent Number 2544185) was for a towing device that attached to the undercarriage of a vehicle, was out of the way of the trunk, and could be hidden away while not in use. As shown in Figure 44, the different cross sectional areas of this design are shown, with the top picture being the full view from the side.

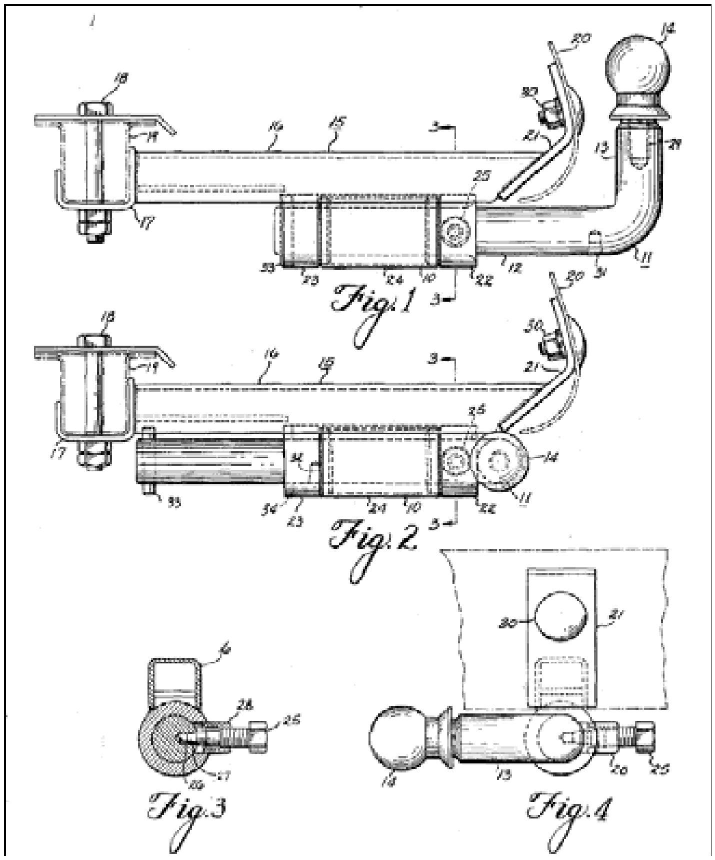

Figure 44: Trailer hitch patent number 2544185

Another important patent contributed to trailer hitch technology was a bumper attached trailer hitch (Patent Number 2671674). This design allowed the trailer hitch to be removed or attached to the rear part of the chassis, where it was out of sight, but still supported loads. The device is simple, cheap, durable, and prevents people from causing damage to their vehicle by accidentally running into objects with the ball mount. This design can be seen in Figure 45.

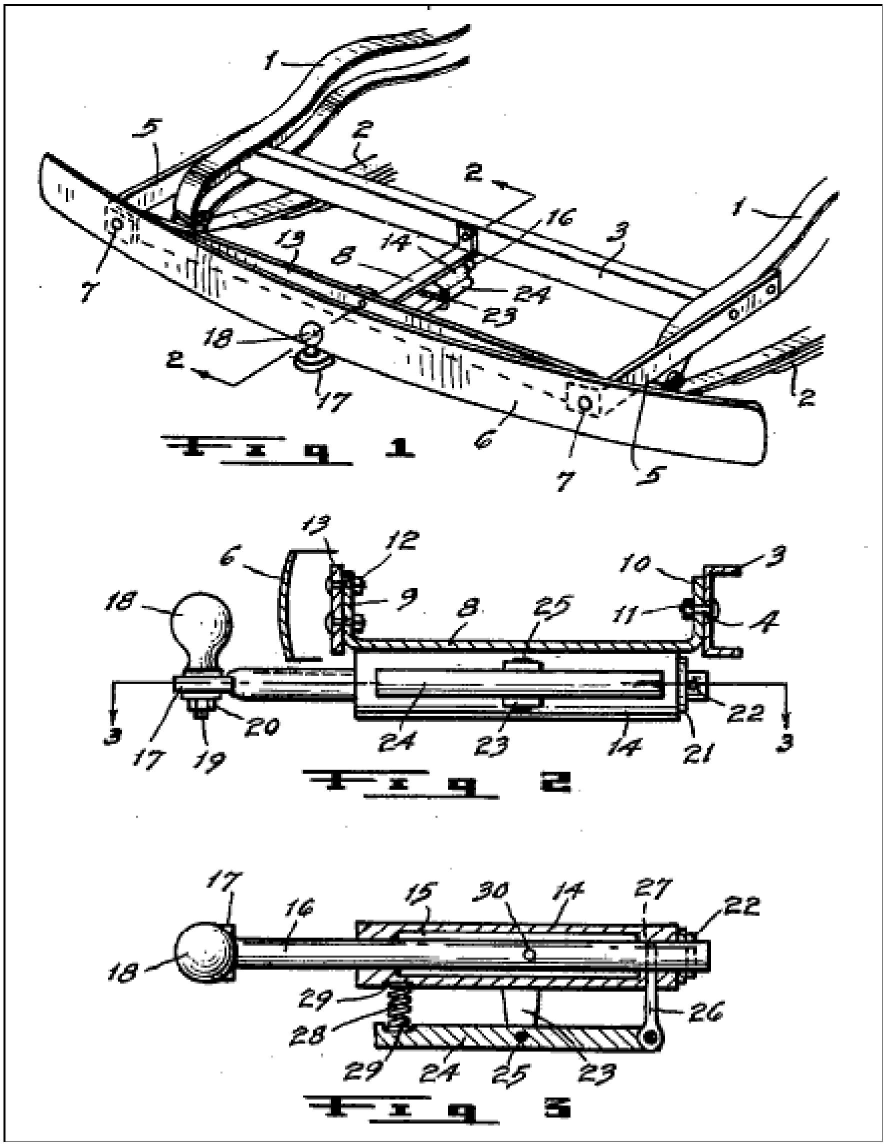

Figure 45: Trailer hitch patent number 2671674

16.5 SAE Standard for Trailer Hitches

To further our literature review, we referenced the SAE Handbook [11]. According to this source, there are four different aspects of loading requirements that a trailer hitch must withstand without incurring failure, which is defined in a slightly different manner for each set of loading requirements.

The first set of loading requirements is for the attachment of the trailer hitch coupling to the trailer's structural attaching member. These details are shown in Table 7 below, specifically for a maximum trailer gross vehicle weight rating (GVWR) of 3500 lb. In this context, failure is defined as loss of attachment, distortion, or fracture that would affect the safe towing of trailers.

Mode of Force Application	Minimum Static Test Load
Longitudinal Tension and Compression	5250 lb
Transverse Thrust	1750 lb
Vertical Tension and Compression	1750 lb

Table 7: Strength test load requirements for attachment of trailer hitch coupling to trailer's structural attaching member

The second set of loading requirements is for the trailer hitch coupling component. As shown in Table 8, this consists of multiple modes of force application. In this context, failure is defined as the occurrence of metal fracture of the coupling assembly. Distortion does not constitute a failure.

Mode of Force Application	Minimum Test Load Requirements
Longitudinal Tension	10500 lb
Longitudinal Compression	10500 lb
Transverse Thrust	3000 lb
Vertical Tension	4500 lb
Vertical Compression	4500 lb

Table 8: Strength test load requirements for trailer hitch coupling to withstand

The third set of loading requirements tests the strength of the trailer hitch. The various force requirements for a weight carrying hitch, such as the Chevy Equinox trailer hitch, are detailed in Table 9. For these tests, failure is defined as loss of attachment between the trailer hitch and the vehicle.

Applied Load	Weight Carrying Hitch Force	
	Force Direction	Force (lb)
Concurrent downward vertical force and compressive longitudinal force	Downward	2125
	Compressive	2125
Concurrent tensile longitudinal force and and downward vertical force	Tensile	2335
	Downward	525
Concurrent compressive longitudinal force and and downward vertical force	Compressive	2335
	Downward	525
Transverse force	Leftward	1200
Transverse force	Rightward	1200

Table 9: Strength test load requirements for trailer hitch to withstand.

Lastly, for the safety chain used in a trailer hitch system, the requirement is to maintain its strength during and after the application of a minimum breaking force. For a Class II trailer classification, this load requirement is an applied tensile load of 3500 lb, to be maintained for a minimum of one minute.

We had anticipated using this information for our FEA and physical analyses, however, by using a stock trailer hitch, these specifications were inherently validated by GM.

16.6 Current Trailer Hitch Bolts

We were informed by the trailer hitch engineer at GM that the bolts used on the current trailer hitch are M12, meaning that the bolts have a nominal diameter of 12 mm and a thread pitch of

1.5 mm (which is the default for bolts whose thread pitch is not explicitly stated). We also learned that the bolts are grade 10.9. This information would be useful if any additional bolts needed to be purchased for the trailer hitch.

16.7 GM Crash Specifications

Based on further discussions with contacts at GM, we determined that there are two standards that relate to our trailer hitch project. The first, set forth by the NHTSA, is the Federal Motor Vehicle Safety Standard (FMVSS) 571.301, which specifies requirements for the integrity of motor vehicle fuel systems [12]. The section that is applicable for trailer hitches is the requirements for a rear moving barrier crash. For our 2005 Equinox, the standard specifies that fuel spillage must not exceed: (i) 28 g from impact until motion of the vehicle has ceased, (ii) a total of 142 g. in the five-minute period following cessation of motion, and (iii) greater than 28 g during any one-minute interval for the subsequent 25 minutes. Originally, we included these fuel spillage requirements as a means to quantify crash specifications, however, due to the large relative distance between the trailer hitch and the fuel tank, we determined that fuel spillage was not an issue in our design.

The second relevant standard was the Bumper Test Protocol, specified by the IIHS, which addresses bumper crash tests [13]. With respect to trailer hitches, the protocol indicates that a trailer hitch is to be removed and its fasteners reattached to the vehicle for testing. Since our design used the same bolts as the original design, we already complied with this standard.

16.8 Challenge X Waiver Information

To investigate the Challenge X Competition waiver requirements and process, our team has contacted Mike Wahlstrom (fjehlik@anl.gov), a representative from Challenge X, about obtaining a waiver to allow modifications to the trailer hitch. He requested that our team send an image of our design, as well as information on the exact placements of the hydraulic line attachments. He will discuss our design with other committee members, and then let us know if our design requires a formal waiver submission. At this point, we have submitted a photographs of our manufactured design and are in the process of receiving feedback from Challenge X authorities. If this feedback is delayed beyond the end of the semester, we will allow our sponsor to take over responsibility for finalizing the waiver.

16.9 Criterion for Corrosion Testing

We referenced the American Society for Testing and Materials (ASTM) standard for "Laboratory Immersion Corrosion Testing of Metals" [14]. This standard gives detailed instructions on acceptable procedures for immersion corrosion tests including specimen preparation, apparatus, test conditions, methods of cleaning the specimens, evaluation of the results, and calculation and proper reporting of corrosion raters. Based on the evaluation and calculation sections, along with consideration of our component geometries, we determined that a maximum of 30% mass reduction was an acceptable criterion for our application.

16.10 Criterion for Frequency Testing

We determined the criterion of 25 Hz for our hydraulic line frequency testing based on discussions with Aaron Sullivan, a Noise and Vibration engineer at GM, and Matt Galligan, the GM engineer who serves as the U of M Challenge X mentor. GM's general rule of thumb for suspension frequency is about 12 to 13 Hz, and to ensure that the frequency of the unsupported hydraulic line length was far enough away from resonant frequency, we were recommended to double this frequency for our test criterion.

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17 TEAM MEMBER BIOGRAPHIES

Beth Bezaire is from Warren, Michigan. Her family includes her parents and younger sister, Andrea, (and if it were up to Beth, they would have a dog, too). Beth will be a first-generation Michigan graduate, while her sister is continuing the family legacy as a junior at Wayne State University.

Beth's path to Mechanical Engineering began as a high school student at the Macomb Math Science Technology Center, where an emphasis on interdisciplinary projects stimulated creativity and teamwork, and her calculus teacher considered tests to be "educational opportunities." As an undergraduate student at the University of Michigan, Beth has developed a concern for energy conservation and sustainability. This motivation, coupled with internship experience at Chrysler, has sparked an interest in advanced powertrain and alternative energy developments in the automotive industry. Her future plans include a Masters degree in Mechanical Engineering.

In addition to educational and career pursuits, Beth is excited to be combining her love for people, volunteering, and travel this summer when she travels to Ecuador for a Habitat for Humanity International trip, where she will be building both houses and relationships.

Claire Carpenter is a dual degree student at the University of Michigan. In April of 2008, she will graduate with two undergraduate Bachelor of Science degrees in Mechanical Engineering and Civil & Environmental Engineering. In combination, these two degrees provide a powerful platform from which to initiate a graduate education focused in Structural Engineering. Including her experiences from her extracurricular activities, structural engineering internships, and research, a Masters of Science in Structural Engineering will give her a theoretical basis of knowledge that will prepare her to apply fresh perspectives and excel in this chosen field. After obtaining a Masters degree, Claire plans to secure a position in the industry. Her primary goal for her professional career is to have the opportunity to address a variety of technical challenges in a team-oriented environment that encourages innovative thinking and new approaches to problem resolution.

Originally from Beverly Hills, Michigan, Claire has lived in Michigan her entire life with her father, Charles, mother, D'Anne, and younger brother, Craig. Outside of the classroom Claire is a co-captain of the University of Michigan Steel Bridge Team. She is also a member of the American Society of Civil Engineers, the American Society of Mechanical Engineers, and the Society of Women Engineers. In the fall of 2006, she was inducted into Chi Epsilon, the National Civil Engineering honor society, and since December of 2006, she has served as the society's secretary. To maintain good health and fitness and meet students in other fields, Claire is very involved in intramural sports as well. She manages soccer teams in the fall and winter, as well as participating on flag football and broomball teams. In her free time, Claire enjoys camping, hiking, and traveling with her family.

Chelsea Jahn was born in Germany and lived there for 4 years. Her family moved to Virginia and then to Michigan in 1998. She loves traveling and has been to different states and countries. One interesting fact is that Chelsea has been to 49 out of the 50 states. She loves staying active and consistently sees herself ready for any obstacle.

Chelsea started at the University of Michigan in the fall of 2004. This April, she is graduating with a Mechanical Engineering Degree and working at Consumers Energy starting June 2nd in Jackson, Michigan. She has always been interested in mechanical engineering from an early age. She continues to be amazed and excited about new things that there are to learn in life. Throughout her college career, she has gotten involved in a variety of activities and leadership roles. Some include, ASME president, Resident Advisor (RA) in Mary Markley, intramural sports, tour guide leader, etc. For her, it is important to obtain a balance between extracurricular activities and school work because this time of your life only happens once. Her favorite quote is, "Live each day to the fullest."

Ann Welton is from Rochester Hills, MI and has lived there in the same house her whole life. She attended the International Academy for high school, which is a public magnet school that allows you to receive an International Baccalaureate(IB) diploma. The emphasis at the school in the sciences and mathematics triggered her interest in engineering. After her senior year of high school, she obtained an internship with General Motors who told her that in order to continue her internship the following summer she needed to major in Electrical or Mechanical Engineering and so she choose Mechanical Engineering. Since that summer she has had three more internships with General Motors. She plans to work at Lockheed Martin outside of Washington D.C. after graduating in April in Mission Services.

Outside of class and work, Ann is on the University of Michigan Figure Skating Team and has been skating since she was 6 years old. She is also an Academic Peer Advisor (APA) in Couzens Hall on campus and has always been active in sports, including tennis and broomball. Ann also loves to read, play games, and travel since she has been to about two-thirds of the US states.

APPENDIX A QUESTIONS FOR DETERMINING PROJECT REQUIREMENTS

A.1 The Challenge X Competition

1. Will every Challenge X team be designing a trailer hitch?
    a. Not necessarily
        i. See Challenge X rulebook for towing competition rules
2. Is the overall goal of the Challenge X program to create a mass-produced vehicle?
    a. No
3. For the Challenge X competition, is there something specific being towed?
    a. How will the trailer hitch be tested?
        i. See Challenge X competition rulebook
4. What is the general history of this U of M team?
    a. How has the team done at past competitions?
    b. What work has the team done on the vehicle to date?
    c. Team has not done very well in the past
    d. Disqualified from towing competition in year 2
    e. Lack of team participation
    f. Parts have broken in the past
5. Why was this project given to an ME 450 team?
    a. Because they have worked with ME 450 in the past
    b. They need design help!
6. Is the vehicle worked on only 8 months out of the year or do the teams work year-round?
    a. Year-round
7. Typically, what are the backgrounds of the students involved in the Challenge X program?
    a. Typically graduate students
    b. Students who are interested in automotive, hydraulics, etc.
    c. Dearborn - 5 master's students
        i. 1 working on regeneration system
        ii. 1 working on emissions
            1. Note: hardest part of emissions is meeting NO_X requirements
    d. 6-12 active members
    e. Javier works on the Challenge X vehicle 10-15 hours per week
8. What happens to the winners of the Challenge X competition?
    a. Are there prizes?
    b. What is the motivation students have for being on the team?
    c. See competition rules
    d. Winners get full-time and/or internship offers
    e. Motivation – get experience and make yourself more marketable

A.2 Design Background

1. Why are we designing the trailer hitch?
    a. We are really more modifying the trailer hitch
        i. Specifically because of the hydraulic lines and oil cooler that were added

    b. We will want to find space/attachment for the hydraulic lines in the design
    c. Vehicle modifications have rendered the current trailer hitch inoperable
    d. ME 450 professors were given 7-8 possible projects
        i. Administration selected the trailer hitch – best "design and manufacture" option
2. Can we take pictures of the vehicle?
    a. Yes
3. What is the level of confidentiality?
    a. Don't worry about it
    b. It's okay for contacts to come to the garage to see the vehicle
    c. Javier will need to be present whenever we want to see the vehicle
4. For benchmarking purposes, what are the competitive vehicles?
    a. Should we consider other commercial vehicles?
    b. Should we consider other teams' designs?
    c. Compare to other automotive manufacturers with trailer hitches
    d. Try to find other teams vehicles and information on their websites
        i. You Tube – Tennessee Challenge X
        ii. It could be hard to get this information from other teams
    e. Other teams may not have modified the trailer hitch – they could have built around it
        i. Therefore, their towing capacity would be the Equinox standard
5. What is the current towing capacity of the vehicle?
    a. Unknown
    b. We will need to calculate it – look up the formula
    c. Right now, it is technically zero because if we attempted to tow something, the trailer hitch would fall off
    d. Car information that may be helpful:
        i. one 55 cc motor – will hopefully be upgraded to 80 cc
        ii. 3700-3800 lbs stock weight
        iii. powertrain limits towing capacity

A.3 Our Design Problems

1. Are CAD documents for the current design available?
    a. Yes
    b. Javier will provide asap
2. Why is the trailer hitch in the way?
    a. What systems are where?
    b. Why do we need to move it around?
    c. Two options:
        1. Keep tow hitch in place and move oil cooler forward
        2. Put oil cooler in and move trailer hitch forward
    d. Check the electrical components inside the trailer hitch
        1. It is unknown whether or not they even work
3. What significance do the oil cooler, hydraulic lines, and exhaust system have on our design?

    a. The hydraulic lines my need to attach to trailer hitch
    b. The oil cooler is in the way of the current trailer hitch position
    c. Exhaust system does not appear to be in the way
4. Does a ball mount for the trailer hitch need to be designed?
    a. No
5. Are you anticipating we will run into any major design problems?
    a. What are your priorities for the problems we need to address?
    b. No problems anticipated
    c. No set priorities
6. What is the likelihood that other systems will be moved in the future that could impact the design of our trailer hitch?
    a. Nothing will be added to the current car
    b. If anything, pieces of the car may leave

A.4 The Design Process

1. What is the timeline for incorporating the trailer hitch?
    a. How soon is our final design needed?
    b. What is the date of the Challenge X competition?
    c. When is the Road Rally?
    d. Our April 10th deadline is before anything would be needed for the competition
2. What units are you working in (metric or English)?
    a. Both – it depends on the part that you're working on
    b. Be alert of this!
    c. Reference CAD drawings
3. Are there materials and/or shop facilities available to help us fabricate?
    a. GM parts are available to us
    b. We will need to work on the car onsite
4. What additional resources are available to our team?
    a. Suppliers – again GM parts available
    b. Sponsors – limited amount of money available – we can look for additional sponsors if we would like
    c. Money – our $400 dollars is pretty much all we get – if we really need more Javier will consider our proposal

A.5 Design Outcomes

1. Other than FEA, are there specific engineering analyses desired or required?
    a. Optimization software
        i. Weight reduction is important!
    b. Being able to compete (i.e., meeting competition rules is a priority)
    c. Crash analysis for 20-30 mph crashes
2. Is our end goal a prototype or a working model?
    a. Working model
3. In general, should our idea be patentable?
    a. Not necessary

4. Are we expected to test the working prototype or model?
    a. It would be good, yes

A.6 Other Notes from the Meeting

1. Trailer hitch is currently made out of mild steel
    a. Aluminum or a higher/thinner grade of steel would be nice
2. Competition organizers like to see use of stock attachment points
    a. These mounting points were designed with crash safety in mind
3. Major goal: improve fuel economy and emissions while meeting stock specifications
    a. Biggest problem with emissions is weight of vehicle
4. Another goal: train the next generation of engineers
5. Consider speed bumps – these will add lots of different forces to the trailer hitch
6. Vehicle make: LT with all-wheel drive
7. GM contact: Matt Gallagan
    a. U of M Challenge X mentor
8. The highest temperature that the hydraulic fluid could reach would be 50˚C

APPENDIX B TECHNICAL BENCHMARKING

	Vehicle	Chevy Equinox	Jeep Liberty	Ford Escape
	Contact Info	Robert Krouse 586-492-9752	John Shapas js104@chrysler.com 313-493-2508	Rich Pietron rpietron@ford.com 313-805-7517
1	What company supplies the trailer hitch?	Thule	Magna	Midway Products
2	What is the weight of the trailer hitch?	26.5 lbs (12 kg)	35 lbs (16 kg)	26 lbs (12 kg)
3	What SAE Class is the trailer hitch?	Class II	Class III	Class II
4	What is the trailer towing capacity?	3500 lbs	5000 lbs	3500 lbs
5	How many bolts are used for attaching the trailer hitch to the vehicle?	6 bolts (two on each end and two in the middle)	6 bolts (3 on each side)	6 bolts (2 M12 on each side connecting to inner rail and 2 M10 connecting into side sill)
6	What type of material is the trailer hitch made of?	Steel, 60 ksi	ASTM A500 Grade B 50 ksi	High-strength, low-alloy steel
7	Does the trailer hitch support other vehicle components?	Wires	Wires	Wires
	If so, how many attachment points are there?	One. Attachment point at electrical box.	One. Attachment point at the electrical connector.	One. Bracket for electrical components.
8	How many steps are there in the trailer hitch manufacturing process?	Four. 1. Fabrication of individual stampings and tubes. 2. All components assembled in weld fixture. 3. Welding. 4. Send out for painting and coating.	Three. 1. Fabrication of individual stampings and tubes. 2. All components assembled in weld fixture. 3. MIG welding.	Made of 8 stamped components. Also requires holes to be punched, and welding operations.
9	How much live load can the trailer hitch sustain?	No information provided.	No information provided.	No information provided.
10	How many pounds of rear load impact can the hitch withstand?	No information provided.	No information provided.	No information provided.

Table B.1: Trailer hitch benchmarking information obtained from automotive companies

APPENDIX C DESCRIPTION OF ENGINEERING CHANGES SINCE DESIGN REVIEW 3

This appendix is a continuation of the concepts in Section 5.3. The sub-sections show additional concepts generated for the middle bracket, end brackets and tubing, and the hydraulic line attachments.

C.1 Additional Middle Bracket Concepts

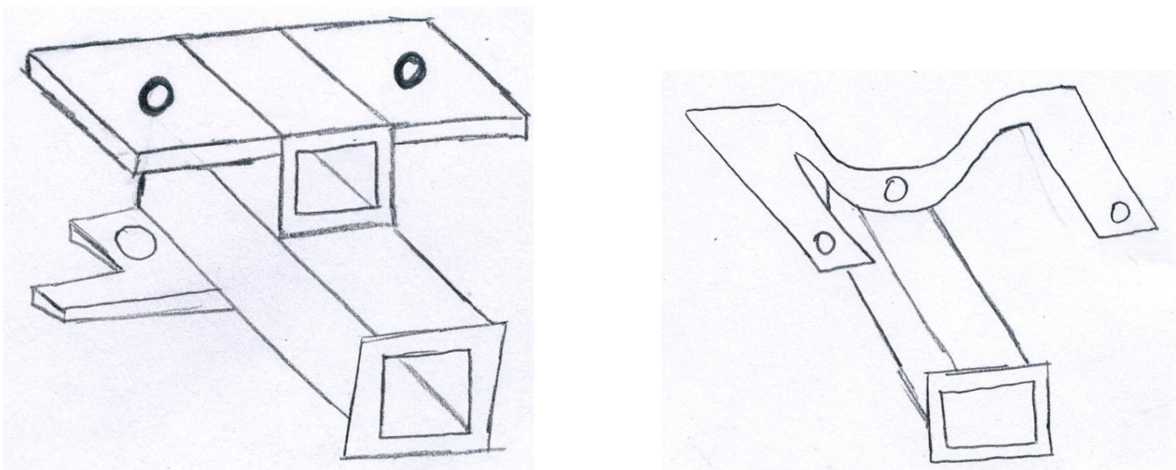

Figure C.1: Square piece with wings (left) and bent-M bracket (right)

C.2 Additional End Bracket and Tubing Concepts

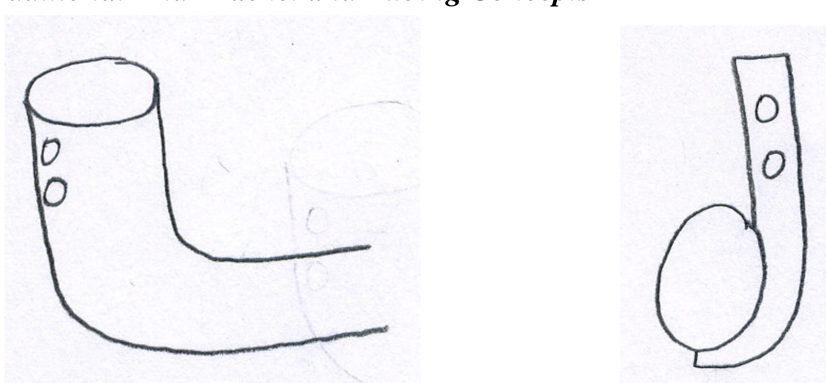

Figure C.2: Bend the trailer hitch bar up (left) and snorkel bracket (right)

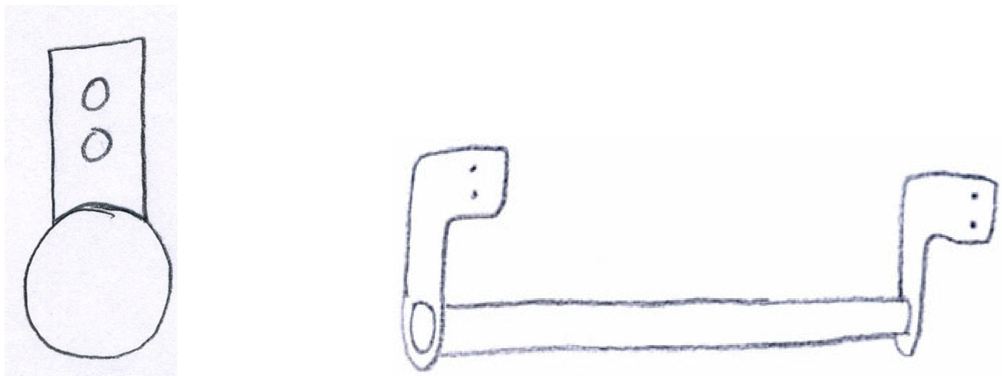

Figure C.3: Stoplight bracket (left) and L-bracket ends concept with straight main bar (right)

Other Ideas:

- Shorten the receiver and push everything back
- Lengthen the brackets to set it down farther in the vehicle and have the hydraulic lines above the hitch

C.3 Additional Fluid Line Attachment Concepts

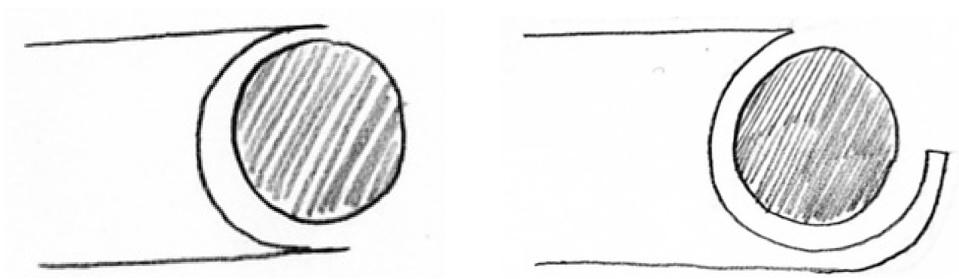

Figure C.4: C-Shape attachment (left) and C-Shape with lip attachment (right)

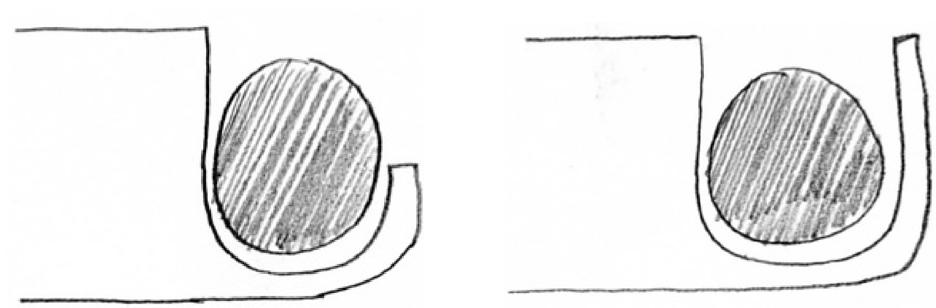

Figure C.5: J-Shape attachment (left) and U-Shaped attachment (right)

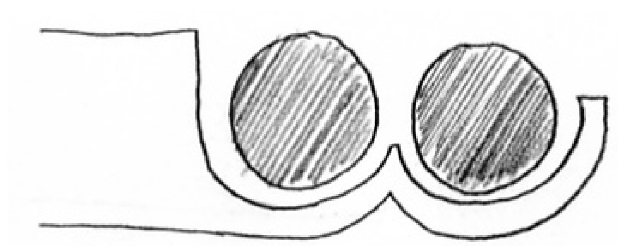

Figure C.6: W-Shaped Attachment

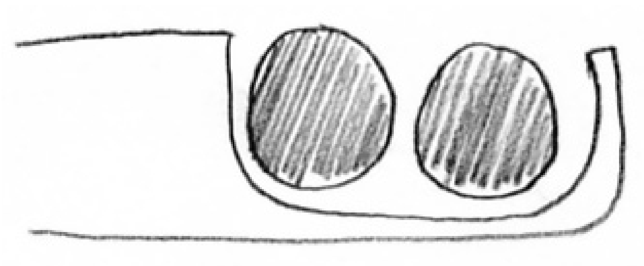

Figure C.7: Two-Line U-Shaped Attachment

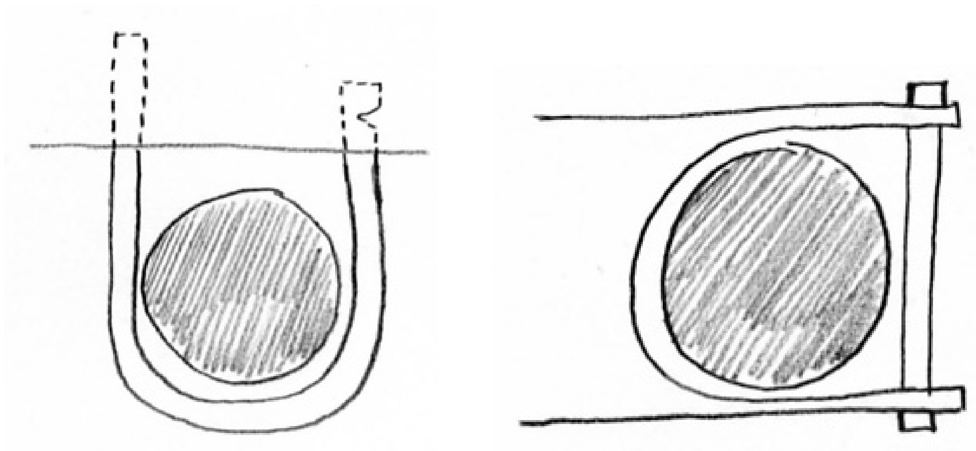

Figure C.8: Lock mechanism (left) and bar lock-secured (right)

APPENDIX D SUB-SYSTEM PUGH CHARTS

To generate the trailer hitch concept variants we used in our entire system Pugh chart, we first used three sub-system Pugh charts to narrow down our ideas for the middle bracket/tubing, end brackets/tubing, and hydraulic/oil cooler line attachment designs.

D.1 Middle Bracket Pugh Chart

Figure D.1 below shows the Pugh chart for the middle bracket component design. As indicated, Designs 2 and 3 were the first and second ranked concepts. We used these two ideas for the middle bracket in generating our overall trailer hitch system variants.

Middle Bracket Design	**Weight**	**Design #1**	**Design #2**	**Design #3**	**Design #4**
Design Criteria		Square with wings	Original	Square with long bolts	M-shaped
No interference with other components	1.6	-	DATUM	-	0
Sustains 3500 lb load	1.6	+		+	-
Lightweight	1.3	-		-	-
Working model tested by April 15	1.1	-		-	-
Uses prior attachment points	1.0	0		0	0
Corrosion resistant	0.8	-		-	0
Easy to manufacture	0.8	-		+	-
Easy to assemble and attach	0.6	-		-	-
Meets GM's crash specifications	0.5	0		0	0
Minimal modification to bumper	0.3	-		-	0
Low cost	0.2	-		+	-
Aesthetically pleasing	0.2	-		-	0
Total Points	1	1.61	0	2.58	0
	0	1.45	10	1.45	4.35
	-1	6.94	0	5.97	5.65
		-5.32	0	-3.39	-5.65
Rank		3	1	2	4

Figure D.1: Sub-system Pugh chart for middle bracket component design.

D.2 End Bracket/Tubing Pugh Chart

Figure D.2 shows the Pugh chart for the end bracket/tubing component design. For this sub-system, we included the top three concepts, Designs 2, 3, and 5, in generating our system variants.

End Bracket/Tubing Design	**Weight**	**Design #1**	**Design #2**	**Design #3**	**Design #4**	**Design #5**
Design Criteria		Forward, then Up	Up, then Forward	Thumbs Up	Snorkel	Original
No interference with other components	1.6	-	+	0	0	
Sustains 3500 lb load	1.6	-	-	0	-	
Lightweight	1.3	0	0	0	0	
Working model tested by April 15	1.1	-	-	-	-	
Uses prior attachement points	1.0	0	0	0	0	D
Corrosion resistant	0.8	-	-	-	-	A
Easy to manufacture	0.8	0	0	-	-	T
Easy to assemble and attach	0.6	0	0	0	0	U
Meets GM's crash specifications	0.5	0	0	0	0	M
Minimal modification to bumper	0.3	-	0	0	0	
Low cost	0.2	+	+	-	-	
Asthetically pleasing	0.2	0	0	0	0	
Total Points	1	0.16	1.77	0	0	0
	0	4.35	4.68	7.10	5.48	10
	-1	5.48	3.55	2.90	3.71	0
		-5.32	-1.77	-2.90	-3.71	0
Rank		5	2	3	4	1

Figure D.2: Sub-system Pugh chart for end bracket/tubing component design.

D.3 Hydraulic and Oil Cooler Line Attachment Pugh Chart

Figure D.3 below shows the Pugh chart for the hydraulic line attachment design. As indicated, Designs 1 and 3 were the first and second ranked concepts, and we used these two ideas in our system variants generation.

Hydraulic/Oil Cooler Line Attachment	**Weight**	**Design #1**	**Design #2**	**Design #3**	**Design #4**
Design Criteria		Coated Steel Hinges	Mesh Screen	Clasps with Padding	Bolted U-rod with cotter pin
No interference with other components	1.9	+	+		-
Structurally support hydraulic lines	1.5	0	-		0
Lightweight	1.5	+	0		-
Working model tested by April 15	1.3	0	0		0
Corrosion resistant	0.9	+	-	DATUM	-
Easy to manufacture	0.9	+	0		0
Easy to assemble and attach	0.7	0	-		0
Meets GM's crash specifications	0.6	0	0		0
Minimal modification to bumper	0.4	+	+		0
Low cost	0.2	+	0		+
Aesthetically pleasing	0.2	0	-		-
Total Points	1	5.74	2.22	0	0.2
	0	4.26	4.44	10	5.37
	-1	0	3.33	0	4.44
		5.74	-1.11	0.00	-4.26
Rank		1	3	2	4

Figure D.3: Sub-system Pugh chart for fluid line attachment design.

D.4 Continuation of System Pugh Chart

Figure D.4 below shows selection matrix for the sixth- through twelfth-ranked concepts for the entire trailer hitch system.

Trailer Hitch System Variants	**Weight**	**Design #9**	**Design #6**	**Design #4**	**Design #11**	**Design #8**	**Design #10**	**Design #12**
Design Criteria		Straight Bar Hinges Orig. Bracket	Thumbs Up Hinges Sq. Bracket	Orig. Bar Clasps Sq. Bracket	Straight Bar Clasps Orig. Bracket	Thumbs Up Clasps Sq. Bracket	Straight Bar Hinges Sq. Bracket	Straight Bar Clasps Sq. Bracket
No interference with other components	1.6	+	-	-	0	-	-	-
Sustains 3500 lb load	1.6	-	+	+	-	+	-	-
Structurally support hydraulic lines	1.3	0	-	0	+	0	0	+
Lightweight	1.3	0	0	-	-	-	0	-
Working model tested by April 15	1.1	-	-	0	-	-	-	-
Corrosion resistant	0.8	+	-	-	0	-	-	-
Easy to manufacture	0.8	-	+	0	-	-	-	-
Easy to assemble and attach	0.6	0	-	-	0	-	-	-
Meets GM's crash specifications	0.5	0	0	0	0	0	0	0
Minimal modification to bumper	0.3	+	0	-	-	-	0	-
Low cost	0.2	0	+	0	-	0	0	-
Aesthetically pleasing	0.2	+	0	-	0	-	0	-
Total Points	1	2.81	2.50	1.6	1.25	1.56	0	1.25
	0	3.75	2.19	3.75	3.59	1.88	3.59	0.47
	-1	3.44	5.31	4.69	5.16	6.56	6.41	8.28
		-0.63	-2.81	-3.13	-3.91	-5.00	-6.41	-7.03
Rank		6	7	8	9	10	11	12

Figure D.4: Continuation of entire system Pugh charts

APPENDIX E FINITE ELEMENT ANALYSIS

To prove that we could decrease the thickness of our curved bar component from 0.25 inches to 0.125 inches, we modeled the component in HyperMesh. We obtained the deformation results shown in Figures E.1 and E.2 for our coarse and fine meshes, respectively. We measured the deformation of the node located in the center of the bar, making sure to use the same node on each model. We found the deformation for the both the coarse and fine meshes to be 1.9 x 10^{-4} inches (reported two significant figures). The percent difference between these two deformation results was less than 0.4%, proving mesh independence.

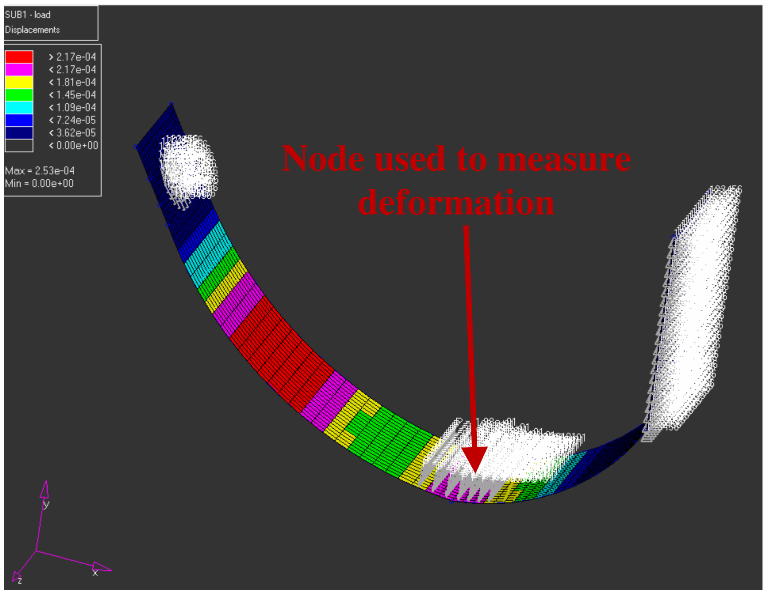

Figure E.1: Deformation results for coarse mesh

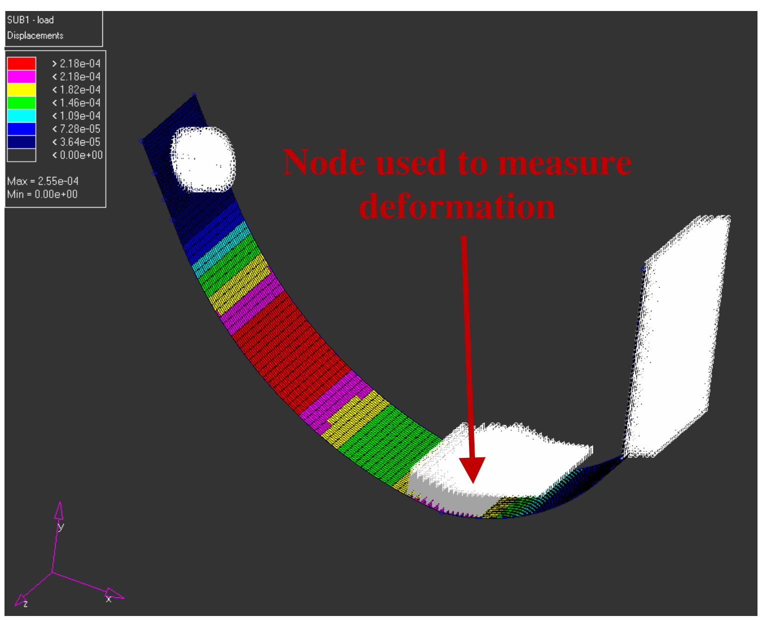

Figure E.2: Deformation results for fine mesh

Figures E.3 and E.4 show the stress results for our coarse and fine meshes. As shown, the maximum stress is just under 3 ksi and occurs below the bolt hole on the right. This stress is much lower than the material yield strength of 50 ksi.

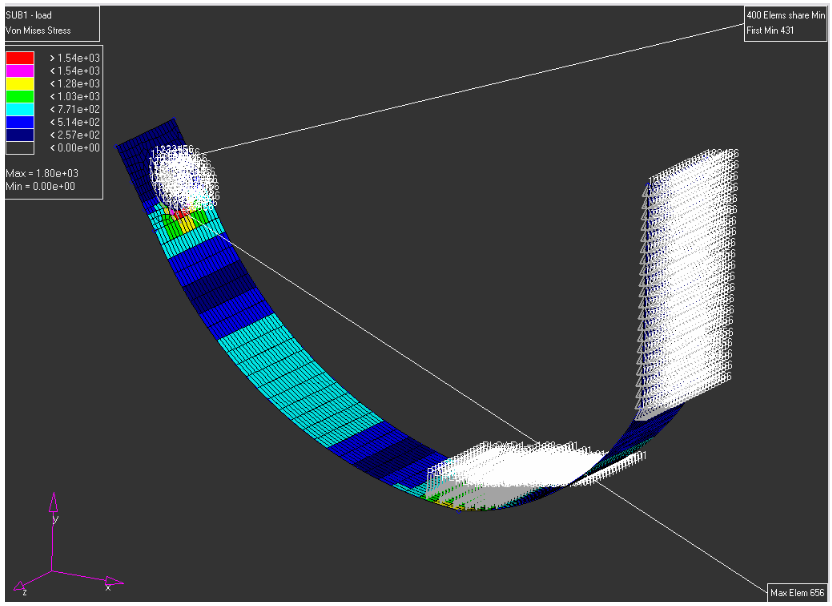

Figure E.3: Stress results for coarse mesh

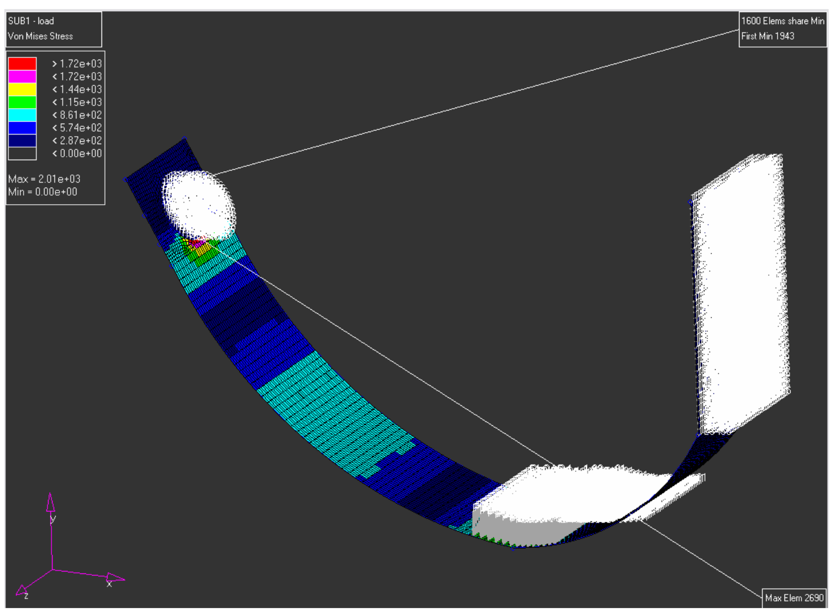

Figure E.4: Stress results for fine mesh

As an additional note, since we have replaced the bolt hole shown on the right in Figure E.4 with welding, we plan to update this FEA analysis with the new constraint for our Final Design Review.

APPENDIX F BILL OF MATERIALS

Item	Quantity	Source	Catalog Number	Cost	Contact
Trailer Hitch Assembly	1	GM Parts Direct	19169825	$171.06	www.gmpartsdirect.com
Curved Bar	2	Alro	1/8" x 1" x 8.7" Rectangular A-36 Hot Rolled Steel	$0.33/each	www.alro.com
Flat Plate	2	Alro	1/8" x 1" x 5.6875" Rectangular A-36 Hot Rolled Steel	$0.22/each	www.alro.com
L-Stock	2	Alro	2" x 2" x 1/8" Structural Angle A-36 Hot Rolled Steel	$0.23/each	www.alro.com
2" Narrow Stainless Steel Hinge	2	Ace Hardware	5297734	$9.00/each	www.acehardware.com
2" Two Hole Pipe Strap	2	Lowe's	55234	$1.78/each	www.lowes.com
Plastic Dip 14.5oz Black	1	Ace Hardware	13275	$7.94	www.acehardware.com
3/4" long and 1/4" diameter Bolts	6	Carpenter Brothers	N/A	$0.11/each	carpenterbrothers.doitbest.com
1/4" diameter Nuts	6	Lowe's	63301	$0.04/each	www.lowes.com

APPENDIX G RESULTS FROM FREQUENCY ANALYSIS

Length of Beam (in)	Length of Beam (ft)	Mass per unit length (slugs/in)	m (slugs)	Applied Force (lbs)	Deflection (in)	k (lb/in)	f (Hz)
4	0.33	0.00383	0.01532	15	0	n/a	n/a
6	0.50	0.00383	0.02298	15	0	n/a	n/a
8	0.67	0.00383	0.03064	15	0	n/a	n/a
10	0.83	0.00383	0.0383	15	0.015625	960.0	25.2
12	1.00	0.00383	0.04596	15	0.03125	480.0	16.3
14	1.17	0.00383	0.05362	15	0.0625	240.0	10.6
16	1.33	0.00383	0.06128	15	0.09375	160.0	8.1
18	1.50	0.00383	0.06894	15	0.15625	96.0	5.9
20	1.67	0.00383	0.0766	15	0.25	60.0	4.5
22	1.83	0.00383	0.08426	15	0.28125	53.3	4.0
24	2.00	0.00383	0.09192	15	0.4375	34.3	3.1
26	2.17	0.00383	0.09958	15	0.53125	28.2	2.7
28	2.33	0.00383	0.10724	15	0.78125	19.2	2.1
30	2.50	0.00383	0.1149	15	0.875	17.1	1.9
32	2.67	0.00383	0.12256	15	1.0625	14.1	1.7
34	2.83	0.00383	0.13022	15	1.25	12.0	1.5
36	3.00	0.00383	0.13788	15	1.3125	11.4	1.4

$$k = \frac{AppliedForce}{Deflection} \qquad m = (MassPerUnitLength)(Length) \qquad f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

APPENDIX H DESCRIPTION OF ENGINEERING CHANGES SINCE DESIGN REVIEW 3

We did not have any engineering changes since the final design presented in Design Review 3. This was because we modified our alpha design concept shortly after Design Review 2 and then manufactured our prototype design with enough time to assess and make the engineering changes necessary to present our final design for the Design Review 3. The only design details added to our final design were the results of our validation analyses and the finalized spacing and location of the hydraulic line attachments on the trailer hitch. Since Design Review 3 focused on the hydraulic line attachment design only, these locations were not specified in Design Review 3, and do not warrant a change notice.

APPENDIX I DESIGN ANALYSIS ASSIGNMENTS FROM LECTURE

The following sections show the results of our Materials Selection, Manufacturing Process Selection, Design for Assembly, Design for Environmental Sustainability, and Design for Safety analyses.

I.1 Material Selection Assignment

The subsections below outline the material selection process undertaken to determine the most suitable material for the six major load-bearing components of our final design and for the coating to be used on the hydraulic line attachments.

I.1.1 Material Selection for the Six Major Final Design Components

All of the six major components in our final design have the basic function of supporting a load while maintaining component stiffness. The stock trailer hitch from GM must be able to support a 3500 lb trailering load, while each of the five components comprising the hydraulic line support mechanisms must be able to support a live load from the hydraulic lines equal to 15 pounds. All six of these components must also support their given loads while undergoing minimal deflection. Therefore, the overall function of the major components in our final design is to economically carry a load while remaining as stiff as possible.

To meet this function, the objective of each of the six major components in the design is to maximize strength and stiffness while minimizing the weight and material cost. Each component of the design must meet the strength requirements specified by the loads above. Based on the geometry of the trailer hitch, the only dimension of the components that is not specified is the thickness of each part. Other constraints on the component design include a minimal weight and minimal material cost.

Using these specified objectives and constraints, two material indices were derived for the major components of our final design. First, to maximize strength while minimizing material cost, the general equations for strength as defined by failure load, F_f, and material cost, C, shown in Equations I.1 and I.2 below, were combined to eliminate the single free variable, h, the thickness of the material. In Equation I.1, C_2 is a constant corresponding to the geometry of the mechanism, b is the width of the material, l is the length of the material, and σ_f is the flexural strength of the material. In Equation I.2, ρ is the density of the material, C_m is cost per unit weight of the material, and b and l are as defined for Equation I.1.

$$F_f = \frac{C_2 b h^2 \sigma_f}{12l} \qquad\qquad C = bhl\rho C_m \qquad\qquad \text{(I.1, I.2)}$$

Equation I.3, shown below, combines Equations I.1 and I.2 into a single equation for minimizing cost. The material dependent component of this equation is separated as Equation I.4, shown below, and is the material index to be maximized in this case.

$$C \geq bl \times \left(\frac{12F_f l}{C_2 b}\right)^{\frac{1}{2}} \times \frac{\rho C_m}{(\sigma_f)^{\frac{1}{2}}} \qquad M_1 = \frac{\sigma_f^{\frac{1}{2}}}{\rho C_m} \qquad \text{(I.3, I.4)}$$

The second material index derived for the six major components of our final design involved maximizing the stiffness, S, of the material while minimizing its mass, m. Equations I.5 and I.6 below, were combined to eliminate the single free variable, h, the thickness of the material. In Equation I.5, b is the width of the material, l is the length of the material, and ρ is the density of the material. In Equation I.6, C_1 is a constant corresponding to the geometry of the mechanism, E is Young's Modulus, and b and l are as defined for Equation I.5.

$$S = \frac{C_1 E b h^3}{12 l^3} \qquad m = bhl\rho \qquad \text{(I.5, I.6)}$$

Equation I.7, shown below, combines Equations I.5 and I.6 into a single equation for minimizing cost. The material dependent component of this equation is separated as Equation I.8, shown below, and is the material index to be maximized in this case.

$$m \geq bl \times \left(\frac{12 S l^3}{C_1 b}\right)^{\frac{1}{3}} \times \frac{\rho}{E^{\frac{1}{3}}} \qquad M_2 = \frac{E^{\frac{1}{3}}}{\rho} \qquad \text{(I.7, I.8)}$$

Using the material indices shown in Equations I.4 and I.8 above, two graphs were created using the *CES EduPack 2007* software. These plots are shown in Figure I.1 below.

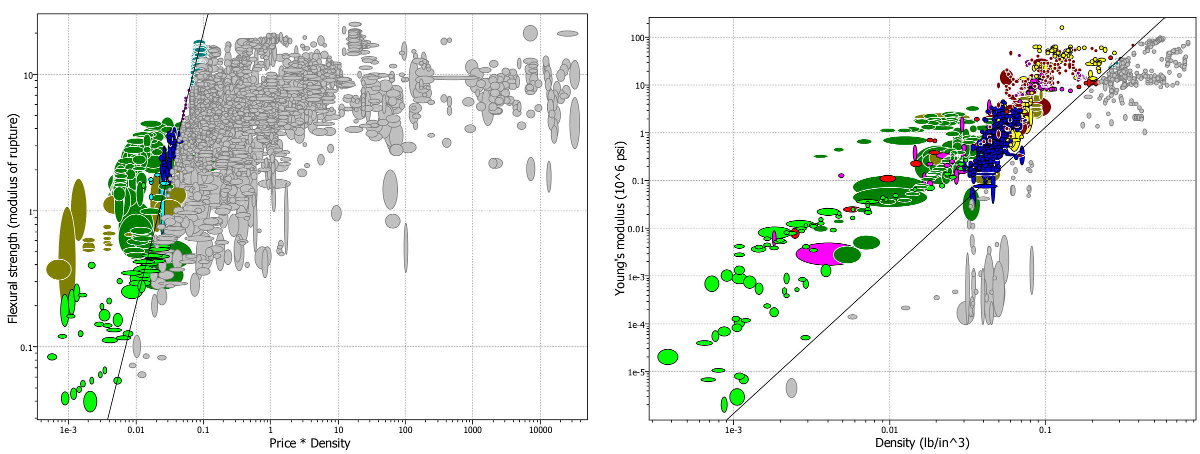

Figure I.1: Plots showing material indices for the six major components of the final design

The results from these plots, along with the hard, limit constraint of a minimum material yield strength of 50 ksi (as defined in Section 4 by our engineering specifications), led to the following top five choices for the material to be used for each of the six major components in our final design:

- Carbon steel

- Low alloy steel
- Nodular graphite cast iron
- Pearlitic malleable cast iron
- Wrought magnesium alloy

Our team's final choice for the material to be used for the six major components of our final design was carbon steel. Specifically, AISI 1030 carbon steel will be used because it is the cheapest of the top materials and it is at least as corrosion resistant (another key customer need as discussed in Section 4) as the other top materials.

I.1.2 Material Selection for Coating of the Hydraulic Line Attachments

We conducted a similar analysis for the material that coats the hydraulic line attachments. The function of this coating is to minimize the amount of corrosion the hydraulic line support mechanisms undergo while attached to the trailer hitch. Therefore, the objectives of the coating material are to maximize corrosion resistance while minimizing the cost and weight. Since there will be a limited amount of coating regardless of the material selection, it is most important to maximize the durability of the coating while minimizing its cost (i.e., minimizing the weight of the coating is a secondary, more negotiable constraint when compared to maximizing durability and minimizing costs).

There are no defined equations or variables within the *CES EduPack 2007* software that refer to the durability of a material. Instead, durability is ranked within the software on a scale from very good to very poor. Since corrosion resistance and cost are of equal importance in this material selection, a plot showing a comparison between these characteristics was created as shown in Figure I.2. Specifically, the durability was evaluated based on corrosion resistance to salt water because this is the compound most likely to corrode the hydraulic line support mechanisms under normal operating conditions.

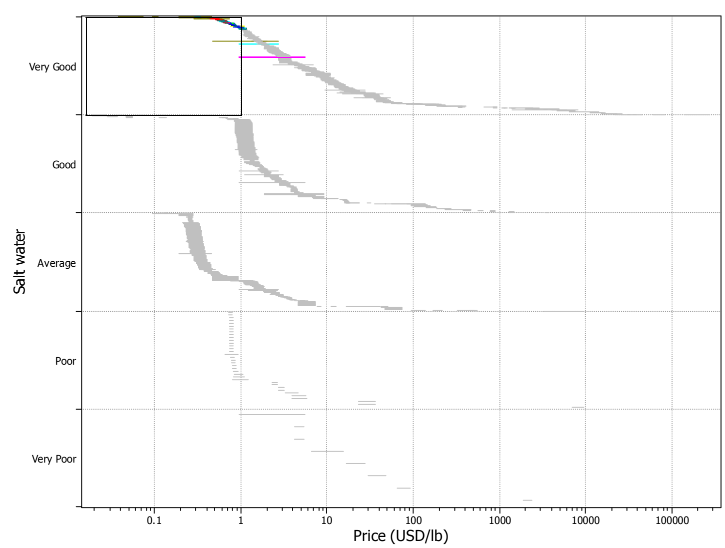

Figure I.2: Plot of durability against cost for the corrosion coating material selection

As shown in Figure I.2 above, by limiting the price per unit weight of the material to less than $1.00 per pound and accepting only materials that were "very good" at resisting salt water corrosion, several material choices were eliminated. To further refine the material choice a hard, maximum limit of 0.033 pounds per cubic inch was placed on the density of the material to eliminate heavier materials. The resulting top five material choices were:

- Butyl rubber
- Ethylene Propylene Diene Terpolymer
- Ethylene Propylene Rubber
- Polypropylene
- Polypropylene Foam

Our team's final choice for the material to be used for the corrosion coating of the hydraulic line support mechanisms was butyl rubber. Of the top five material choices it was the most resistant to salt water corrosion. It also displayed at least average corrosion resistance against fresh water, weak acids, strong acids, weak alkalis, strong alkalis, organic solvents, and UV radiation. Secondly, butyl rubber's typical use in car tires implies that GM will already be familiar with this material. Therefore, mass production of the corrosion coating can be more easily achieved.

I.2 Manufacturing Process Selection

In today's society there is a large demand for improving fuel economy in all vehicles on the road, leading to an increased interest in hybrid vehicles. Currently, the hydraulic hybrid system is not widely implemented. However, if hydraulic hybrid vehicles become a mass-produced product, our hydraulic line attachment design for the trailer hitch of the Chevy Equinox would be useful to society. Since these vehicles would initially make up only a small percentage of vehicles produced by automotive companies, our target production is 1000 hydraulic line attachments.

As determined by our Material Selection (see Section I.2), we have chosen AISI 1030 carbon steel to manufacture the components of our final design and butyl rubber to coat the components and protect against corrosion. Using the CES manufacturing process selector for AISI 1030 carbon steel, we determined that it would be best to use a sheet manufacturing process, specifically stamping, to manufacture our final design. This process is ideal for our mechanism because it is typically used to form complex shapes. There are four forms to the stamping process, deep drawing, blanking, bending, and stretching, which are shown in Figure I.3.

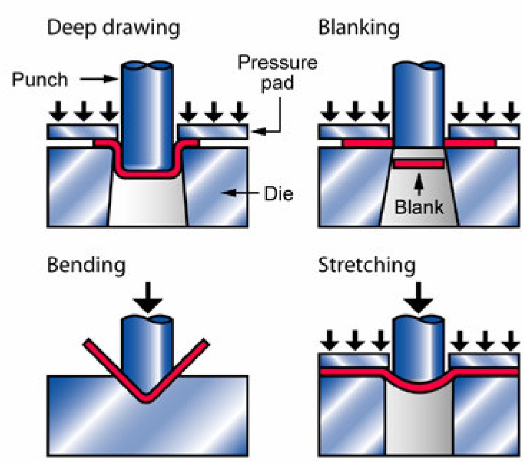

Figure I.3: Four types of applications for the stamping manufacturing process

Out of the four applications to the stamping manufacturing process, we would use a combination of bending and stretching to form one unit. Stamping is commonly used with metals, particularly steel and shapes with holes, tabs, recesses, cavities, and raised sections are standard. Since the shape of the curved bar in our mechanism is unique and hard to replicate, having a die of our shape would be the most ideal. Table I.1 lists some of the physical attributes to the stamping process.

Mass Range	2.205e-3 - 2.205 lb.
Range of Section Thickness	0.01181 - 0.1969 in.
Tolerance	3.937e-3 - 0.0315 in.
Roughness	0.01969 - 0.4921 mil.

Table I.1: Physical attributes of stamping process

The stamping manufacturing process also is applicable to our final design because each of our mechanisms is currently 0.9 lb. and fits within the mass range as well as having a target production value of 1000 units. The relative cost index of our manufacturing process is 14.98-32.95 per unit which is shown in Figure I.4.

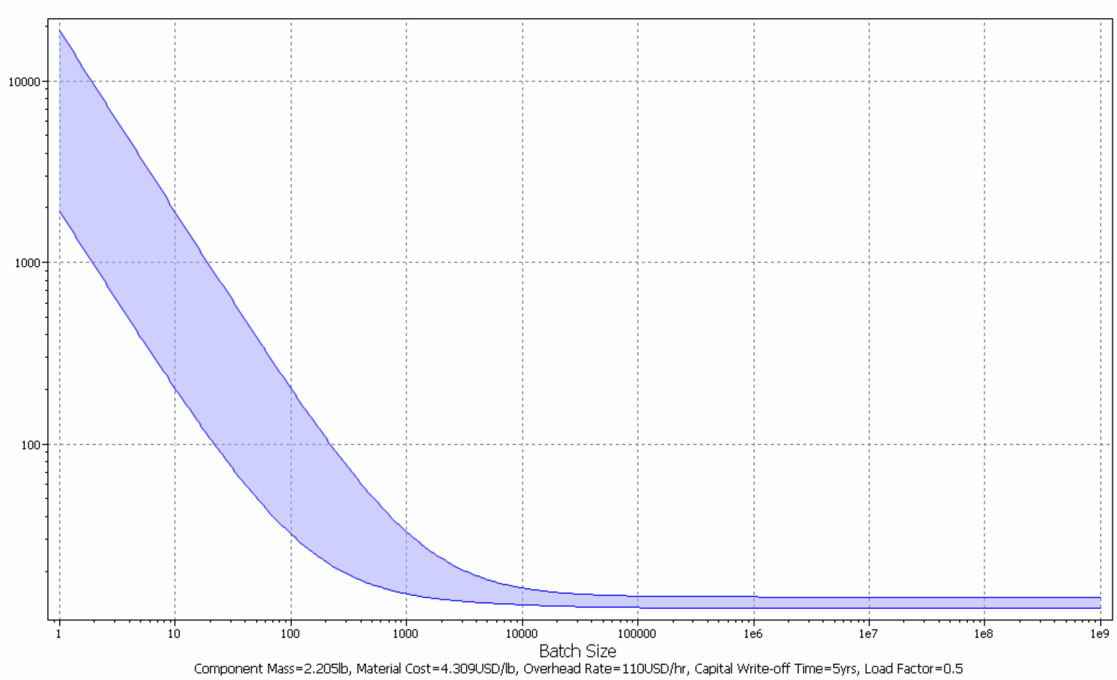

Figure I.4: Relative Cost Index for stamping manufacturing process of AISI 1030

The CES manufacturing process selector provided the capital write off time of 5 years as well as the material cost of 4.309 USD/lb. Table I.2 shows the additional modeling costs for the stamping manufacturing process.

Capital Cost	9426 – 9.426e4 USD
Material Utilization Fraction	0.7 – 0.8
Production Rate (units)	200 – 2000 per hour
Tool Life (units)	1e4 – 1e5
Tooling Cost	1885 – 1.885e4 USD

Table I.2: Modeling cost for the stamping manufacturing process

Overall, the stamping process is the most ideal for our final design support mechanism in order to produce 1000 units.

We discovered through the CES software that the best manufacturing process for butyl rubber for our application is a surface treatment process, specifically water-based painting, to cover the final design components in order to prevent corrosion. Figure I.5 shows the process of the water-based painting.

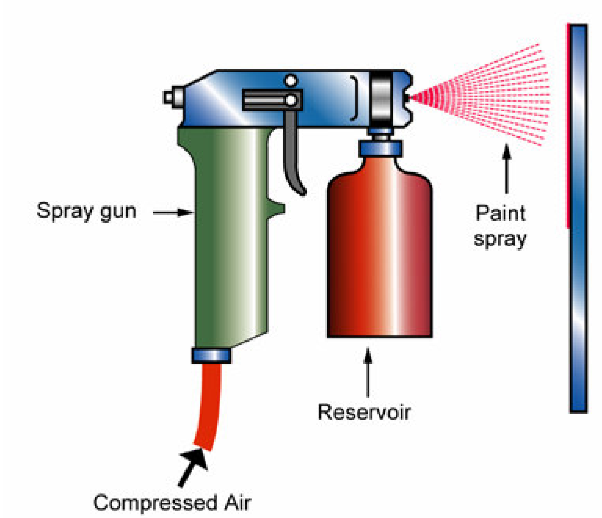

Figure I.5: Diagram of water-based painting process to be used for butyl rubber

The relative equipment cost is medium, tooling cost is low, and the time before handling is 500-5000 seconds. The water-based painting manufacturing process gives good weathering resistance which is important to our design because we want to prevent against corrosion. Table I.3 below contains physical characteristics of the water-based painting process.

Processing Temperature	62.6 – 170.6 F
Curved Surface Coverage	Good
Coating Thickness	0.3937 – 7.874 mil.
Surface Hardness	5 – 10 HV

Table I.3: Physical attributes of the water-based painting manufacturing process

Overall, water-based painting is the best manufacturing process for our mechanisms on the Chevy Equinox trailer hitch to support the hydraulic lines.

I.3 Design for Assembly

To reduce the number of parts in our design and to simplify the assembly of the remaining parts, we have completed a Design for Assembly (DFA) analysis using the Boothroyd-Dewhurst method. This method is based on the following assumptions for manual handling: (i) the parts are presented in bulk and randomly oriented, and (ii) parts are added one at a time. We have analyzed our prototype design as our original design, and then used these results in a re-design which was used in generating the final design for our hydraulic line attachment.

First, we conducted our original DFA analysis for our prototype design. Figure I.6, shows the original DFA worksheet completed for this analysis. To calculate the design efficiency, η, we used Equation I.9, where N_m is the theoretical number of minimum parts and T_m is the actual assembly time in seconds. As shown, the design efficiency for our original design was 38.5%.

$$\eta = \frac{3 \cdot N_m}{T_m} \tag{I.9}$$

1	2	3	4	5	6	7	8	9	
Part I.D. No.	Number of times the operation is carried out consecutively	Two-digit manual handling code	Manual handling time per part	Two-digit manual insertion code	Manual insertion time per part	Operation time in seconds [2]*([4]+[6])	Operation cost in cents 0.4*[7]	Figures for estimation of minimum number of parts	Name of Assembly
1	1	30	1.95	00	1.5	3.45	1.38	1	C-shaped component
2	1	10	1.5	06	5.5	7	2.8	1	Flat bar
3	1	10	1.5	06	5.5	7	2.8	1	Hinge
6	1	10	1.5	38	6	7.5	3	1	Bolt between Hinge, Flat Bar, and C-shaped component
4	1	30	1.95	06	5.5	7.45	2.98	1	Curved bar
6	1	10	1.5	38	6	7.5	3	1	Bolt between Curved Bar and Hinge
5	1	30	1.95	06	5.5	7.45	2.98	1	L-bracket
6	1	10	1.5	38	6	7.5	3	1	Bolt between L-bracket, C-shaped and Flat Bar
6	1	10	1.5	38	6	7.5	3	0	Bolt between L-bracket and Curved Bar
						Tm	**Cm**	**Nm**	**Design Efficiency**
						62.35	24.94	8	0.385

Figure I.6: DFA worksheet for original (prototype) design

Next, we used the results of our original design to develop an improved design and method for assembly. We completed a test for minimum number of parts, as shown in Figure I.7.

Test for Minimum Number of Parts											
	First Component:	C-shaped	C-shaped	C-shaped	C-shaped	Flat Bar	Flat Bar	Flat Bar	Hinge	Hinge	L-bracket
	Second Component:	Flat Bar	Hinge	L-bracket	Curved Bar	Hinge	L-bracket	Curved Bar	L-bracket	Curved Bar	Curved Bar
1	Do parts move relative to each other?	No	No	Yes	Yes	No	Yes	Yes	Yes	No	No
2	Must these parts be made of different materials?	No	Yes	No	No	Yes	No	No	Yes	Yes	No
3	Would combination of these parts prevent assembly or disassembly of other parts?	Yes	No	Yes	Yes	No	Yes	Yes	Yes	No	No
4	Has servicing of the assembly been adversely affected?	No	No	No	No	No	No	No	No	No	No
	Consider combining these parts?	No	No	No	No	No	No	No	No	No	Yes

Figure I.7: Test for minimum number of parts based on prototype design

Based on our test for minimum number of parts, we determined that the only parts we should consider combining were the L-bracket and the curved bar. We did not fabricate one integrated piece due to the difficulties in manufacturing that would arise from bending a single piece of flat stock into a right angle. Therefore, to increase assembly efficiency, we decided to weld the L-bracket and curved bar together, thereby eliminating the bolt between these two components. From an assembly standpoint, this is essentially combining the two parts together. We were also able to improve the assembly process by assembling the components in a different order. By starting the assembly process with a bolt, it allows the bolt holes of the hinge, flat bar, and C-shaped component to be aligned, which reduces insertion time. These changes are reflected in the DFA worksheet analyzing our re-design shown in Figure I.8.

1	2	3	4	5	6	7	8	9	
Part I.D. No.	Number of times the operation is carried out consecutively	Two-digit manual handling code	Manual handling time per part	Two-digit manual insertion code	Manual insertion time per part	Operation time in seconds [2]*([4]+[6])	Operation cost in cents 0.4*[7]	Figures for estimation of minimum number of parts	Name of Assembly
6	1	10	1.5	38	6	7.5	3	1	Bolt between Hinge, Flat Bar, and C-shaped component
3	1	10	1.5	00	1.5	3	1.2	1	Hinge
2	1	10	1.5	00	1.5	3	1.2	1	Flat bar
1	1	30	1.95	00	1.5	3.45	1.38	1	C-shaped component
4	1	30	1.95	06	5.5	7.45	2.98	1	Curved bar and L-bracket assembly
6	1	10	1.5	38	6	7.5	3	1	Bolt between Curved Bar and Hinge
6	1	10	1.5	38	6	7.5	3	1	Bolt between L-bracket, C-shaped and Flat Bar
						Tm	Cm	Nm	Design Efficiency
						28.9	11.56	5	0.519

Figure I.8: DFA worksheet for re-design (final)

As shown, the design efficiency for our redesign is 51.9%, which is a significant improvement from our original design efficiency of 38.5%.

I.4 Design for Environmental Sustainability

From our Materials Selection process, carbon steel and butyl rubber were our two selected materials. This Design for Environmental Sustainability focuses on the environmental impact of one hydraulic line attachment. For our steel analysis, we used a mass of 0.2138 kg, which considers the mass of both the curved bar and the flat bar. For our rubber analysis, we used a mass of 0.0223 kg, which was calculated based on an estimate of the amount of rubber required for three coats applied to the curved bar, flat bar, and C-shaped components. In SimaPro, we chose C55 I steel as a material similar to carbon steel, and we chose EPDM rubber ETH U as a material similar to butyl rubber.

Figure I.9 shows the total mass of air emissions, water emissions, use of raw materials, and (solid) waste. These results indicate that the C55 I steel has a greater mass air emissions, raw material usage, and (solid) waste, while the EPDM rubber ETH U has greater water emissions.

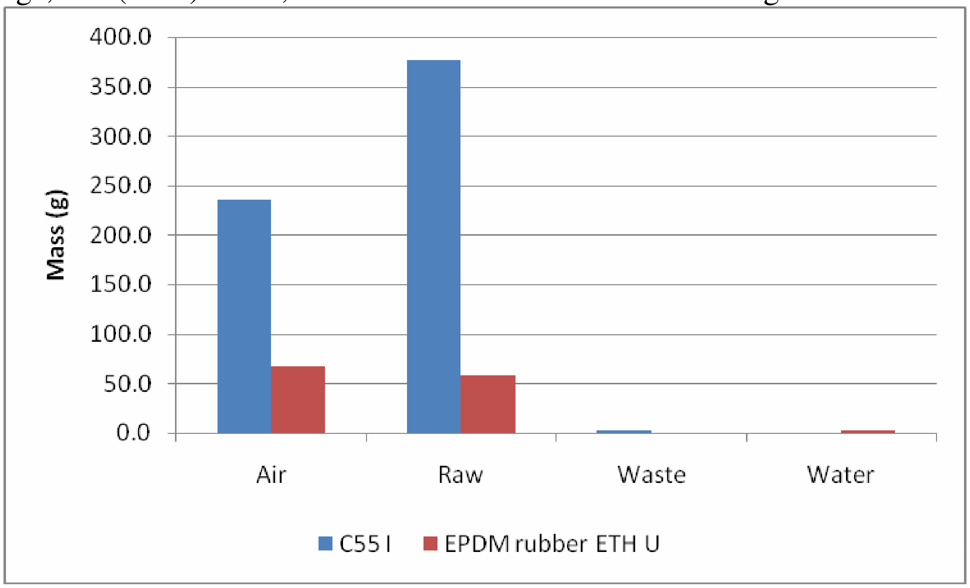

Figure I.9: Total mass of air and water emissions, use of raw materials, and (solid) waste.

Figure I.10 shows each material's impact on the environment within each of the EcoIndicator 99 damage classifications. These results indicate that the C55 I steel has a greater impact on minerals, land use, acidification/eutrophication, ecotoxicity, climate change, and respiratory inorganics, while the EPDM rubber ETH U has a greater impact on ozone layer, radiation, respiratory organics, and carcinogens.

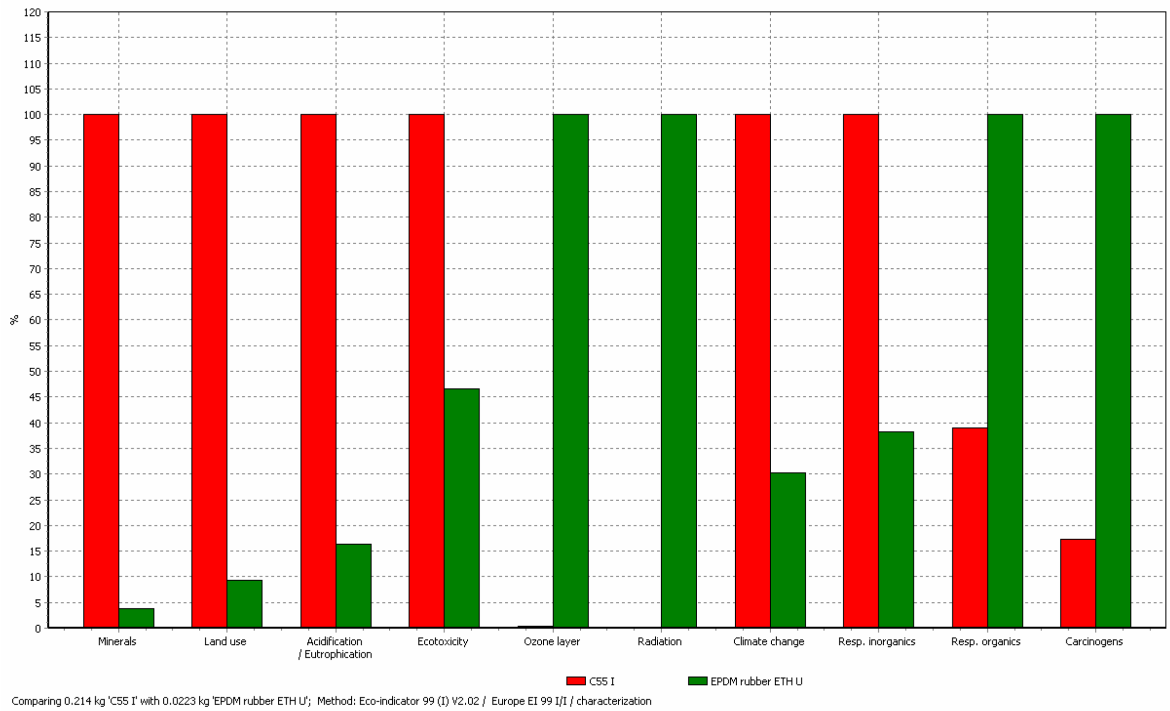

Figure I.10: Relative impacts in disaggregated damage categories

Figure I.11 shows the relative importance of the damage meta-categories based on the EcoIndicator 99 point values. This analysis indicates that Resources is likely to be the most important category from the analysis of C55 I steel. For the EPDM rubber ETH U, Human Health has a slightly greater normalized score than Resources. The score for Ecosystem Quality is lowest for both materials.

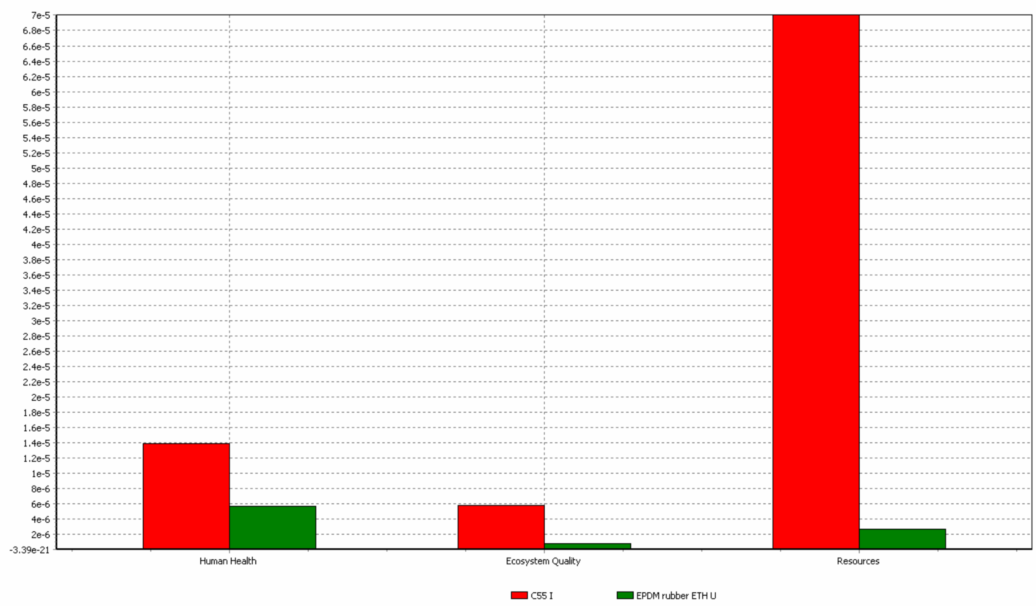

Figure I.11: Normalized score in human health, eco-toxicity, and resource categories

Figure I.12 shows the relative EcoIndicator 99 “point values,” indicating that the C55 I steel will have a bigger impact when the lifecycle of the whole product is considered.

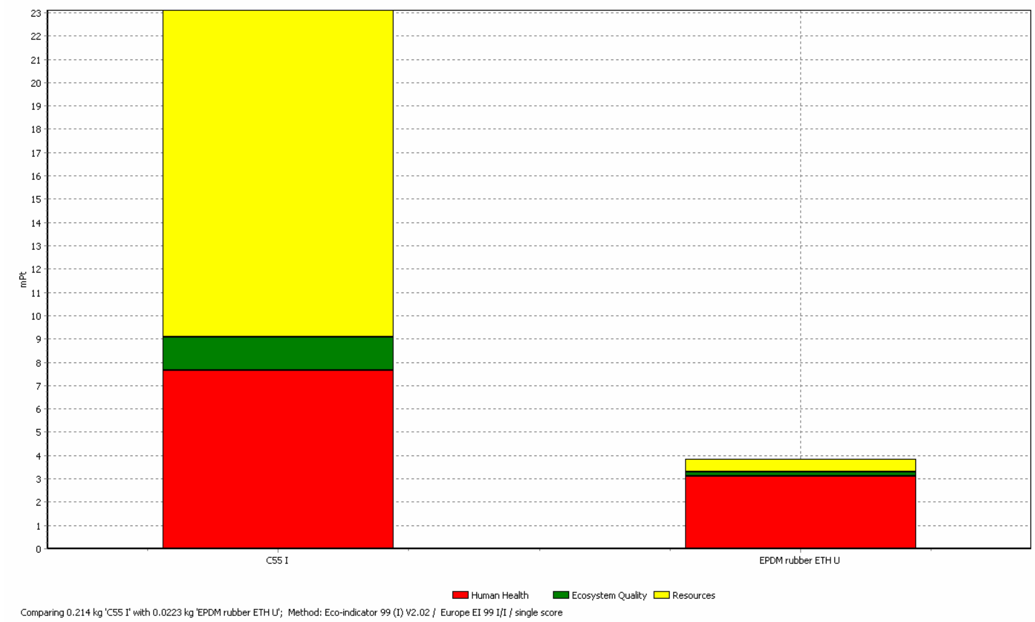

Figure I.12: Single score comparison in EcoIndicator 99 “points”

Based on our SimaPro analysis, the C55 I steel has a greater environmental impact, both on its own and from a life cycle analysis standpoint.

I.5 Design for Safety

Failure Modes and Effects Analysis (FMEA) looks at failure modes from an analytical approach through a set procedure and classification system, and also assesses the consequences of these failures. The purpose of FMEA is to determine where the greatest risk might arise and design around this issue so that a problem never occurs. The basic steps to using the FMEA tools are:

- Assign a label to each process or system component
- List the function of each component
- List potential failure modes
- Describe effects of the failures
- Determine failure severity
- Determine probability of failure
- Determine detection rate of failure
- Assign RPN
- Take action to reduce the highest risk

Some examples of failure modes are corrosion, buckling, fatigue, leaking, etc.

Risk assessment is targeted at reducing task-based risks to people. It analyzes the what, why, and how, as well as how much of safety risk exists for the users. The basic steps to performing a risk assessment are:

- Identify hazards
- Assess risk
- Reduce risk

Identifying the hazards is very useful and should focus on what tasks the user will do and what hazards they may encounter. Assessing the risks can be done different ways based on the system being evaluated. Some common methods of evaluation are qualitatively, semi-quantitative, and quantitative. Using a risk scoring method brings structure to a subjective analysis but requires comfort with sticking to the scoring method. The overall goal is to reach an acceptable risk, i.e. risk that remains even after protective measures have been taken but that is accepted in a given context. Acceptable risk is also the point at which to stop addressing a specific hazard so that the least amount is money is spent while still providing a safe atmosphere. Zero risk does not exist, so knowing when you've reached an acceptable risk is important. Reducing risk can also be accomplished through a Hazard Control Hierarchy which is approached through:

1. Eliminate by **design**
2. Use **guard** systems
3. Provide **warnings** systems
4. Use **training** (instructions)
5. Provide personal protective equipment (**PPE**)

The hope is that by the end of the risk assessment, risk is reduced to acceptable risk and that there is a roadmap to continue risk reduction activities.

Based on these ideas, an analysis of our project was done using the DesignSafe program. The risk assessment of our project was built into this analysis. As indicated by our results in Table I.4, protective measures can be taken to reduce our risks to an acceptable measure. All of these measures provide an acceptable level or risk at a low cost. Obviously, no measure can completely eliminate risk. The major risk is potential sharp edges on the attachment puncturing the hydraulic line. This could cause hydraulic fluid to leak, thereby hindering vehicle operation, causing hazards to the user, and harming the environment.

designsafe Report

Application:	Design and Integration of a Trailer Hitch	Analyst Name(s):	Ann Welton
Description:		Company:	
Product Identifier:		Facility Location:	
Assessment Type:	Detailed		
Limits:			
Sources:			

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level
All Users All Tasks	mechanical : stabbing / puncture Sharp edges or rubbing against the hydrualic line may cause them to puncture	Catastrophic Frequent Unlikely	High	Apply a rubber coating to eliminate sharp edges and hold the line in a secure place that no excessive rubbing occurs.	Catastrophic Remote Unlikely	Moderate
All Users All Tasks	mechanical : break up during operation Loss of the bolts during operation will cause the attachment to break apart	Slight Remote Unlikely	Low	Use snaps instead of bolts which won't fall off.	Slight None Unlikely	Low
All Users All Tasks	electrical / electronic : insulation failure Environmental Factors, rubbing, pull-out, etc. may cause an insulation failure of the wires to the electrical box.	Slight Remote Negligible	Low	Use an insulator that will not be affected by environmental factors.	Slight Remote Negligible	Low
All Users All Tasks	electrical / electronic : shorts / arcing / sparking Improper wiring or pull-out of wires from or to the electrical box.	Serious Remote Unlikely	Moderate	Have a trigger if a short is detected in the wiring.	Serious Remote Negligible	Low
All Users All Tasks	electrical / electronic : improper wiring Design error or manufacturing error in building up the wiring for the electrical box.	Serious Remote Unlikely	Moderate	Check all wiring before handing off to a customer that way errors can be fixed before use.	Serious Remote Negligible	Low
All Users All Tasks	noise / vibration : noise and vibration Bumps in the road can cause the hydraulic line to bump against the attachment.	Minimal Frequent Unlikely	Moderate	Apply rubber coating to decrease the amount of noise and have attachments close enough to not allow slack.	Minimal Occasional Unlikely	Low
All Users All Tasks	environmental / industrial hygiene : corrosion Road salt or contaminated water splashing up from the road can corrode the metal of the attachments.	Minimal Occasional Probable	Moderate	Rubber coating or other weather-proof coating over the whole attachment.	Minimal Remote Unlikely	Low
All Users All Tasks	chemical : hazardous production materials The rubber that the attachment parts is dipped into is made of carcinogenic material.	Catastrophic Frequent Probable	High	Use a different coating that isn't harmful.	Minimal None Negligible	Low
All Users All Tasks	fluid / pressure : hydraulics rupture Sharp edges or rubbing against the hydraulic line may cause the hydraulice line to rupture.	Catastrophic Frequent Unlikely	High	Apply a rubber coating to eliminate sharp edges and hold the line in a secure place that no excessive rubbing occurs.	Catastrophic Remote Unlikely	Moderate

Table I.4: Results of risk assessment completed in DesignSafe software